Status of the Recycler, Commissioning and Upgrades in progress

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ACC

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- Introduction to the Recycler
- Modifications and upgrades
- The Status and present understanding of the Recycler.
- The upgrade being done during the Nov.- Jan 01 Shutdown
- Commissioning plans
- Summary

Introduction

- Recycler Ring is designed to store and cool antiprotons from the Accumulator via Main Injector. In the final configuration it will also Recycle antiproton from the Tevatron.

- The overall design goal is to increase the production rate of the antiproton in the Fermilab Accelerator complex by keeping the stack size in the Accumulator low. This is accomplished by transfer of Antiproton from the Accumulator to the Recycler at a regular interval (> 60 min.).

- The Recycler is designed to store a total of about 2e12 antiprotons to support the Run-II plans.

- The design lifetime of the Recycler is 10 hours without cooling and about 100 hours with cooling.

Status of the Recycler

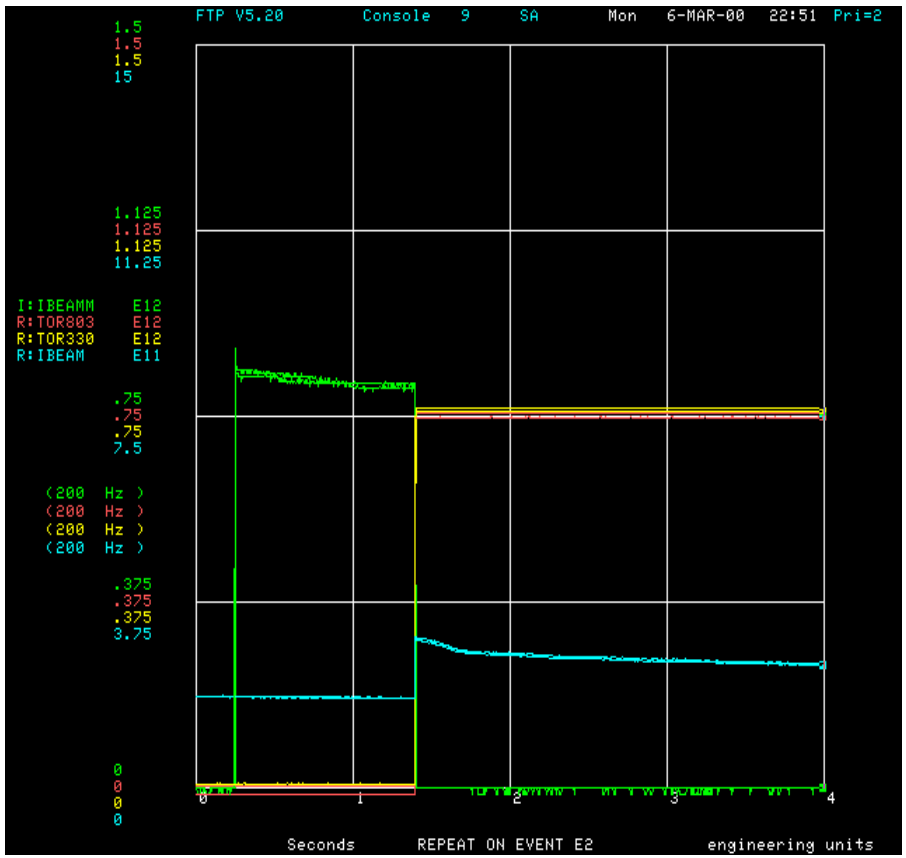
- We have been performing all the RR commissioning using proton from the Booster-->MI-->RR at 8 GeV.
- Beam is injected into the Recycler using RR30 transfer line. This line will be used from pbar extraction during collider operation.
- The efficiency of the transfer line RR30 has been close to 100% since summer of 99. We can run this line with all corrector off to get 100% transmission in the transfer line. But correctors are needed to properly inject beam into the Recycler.
- The injection efficiency of the proton beam in the Recycler has been > 90% as measured by TOR330 and TOR213.

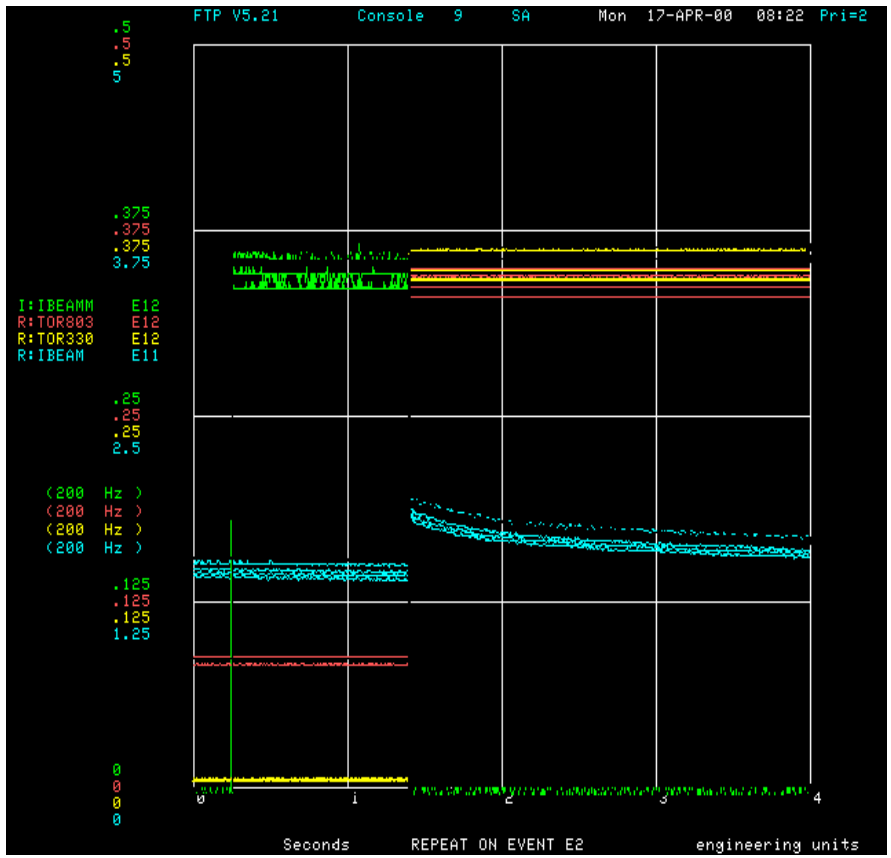
Status of the Recycler...

- During the course of last 1.5 year measurements and Accelerator physics calculations have revealed several problems with the Recycler construction and installation.
  - Recycler End Shims replacement to properly take into account of sextupole feed down effect.
  - Removal of the magnetic heater strips to reduce the higher order multipoles in the Recycler Magnets, including large sextupole.
  - Realignment of the Recycler Magnets.
  - Improvement of vacuum to ~1e-10 Torr.
- Major concern has been loss of beam in the Recycler in first 5-10 turns.

Status of the Recycler...

- After these major work in the tunnel during the Feb. 00 shutdown the Recycler circulating beam efficiency and lifetime started increasing.





Recycler Improvements

• We have made several improvements in the Recycler since Feb 00 shutdown. Most of these work has been done in parallel as our understanding of the Recycler progressed.

- Stable BPM
- Recycler Injection and orbit
- Injection orbit coupling
- Magnet Moves to improve the closed orbit.
- Closed orbit improvements using correctors. Additional correctors.
- Alignment of beam pipes and BPM
- New magnetic Shielding in MI30 straight section
- Software: injection, orbit, lattice analysis, magnet moves, tune etc
- Aperture Scan and centering of the beam in Aperture
- Lattice studies and operating point changes
- RF manipulations

Recycler BPM

- During the Feb 00 shutdown a change in the Recycler BPM preamps were made. This change was in the resonance frequency of the preamps from 53 MHz to 7.5 MHz.

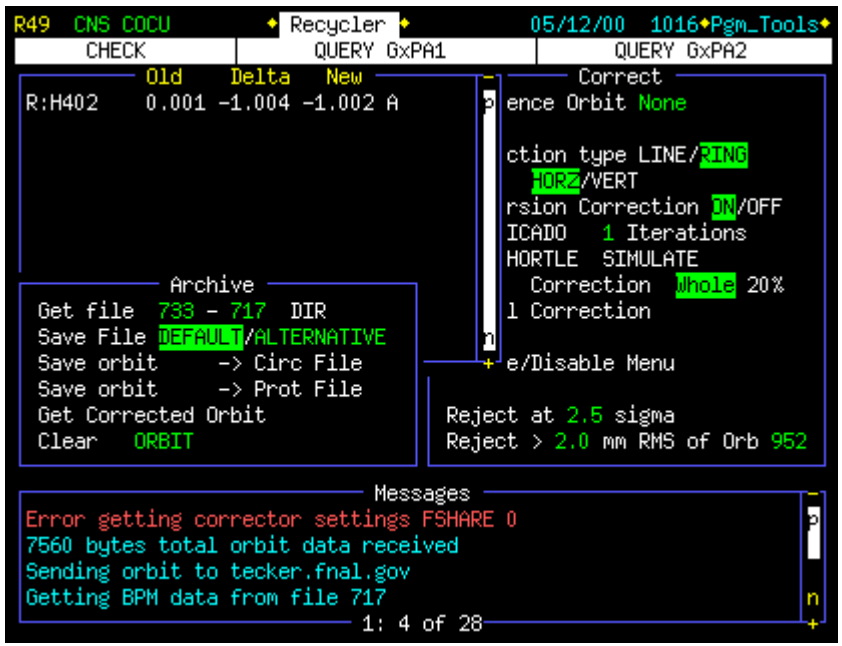
- This change lead to change the way we inject beam into the Recycler. For a stable operation of the BPM system we transfer the MI Beam from 53 MHz to 2.5 MHz in MI. The 2.5 MHz coalesced proton beam is transferred into the Recycler 2.5 MHz buckets.

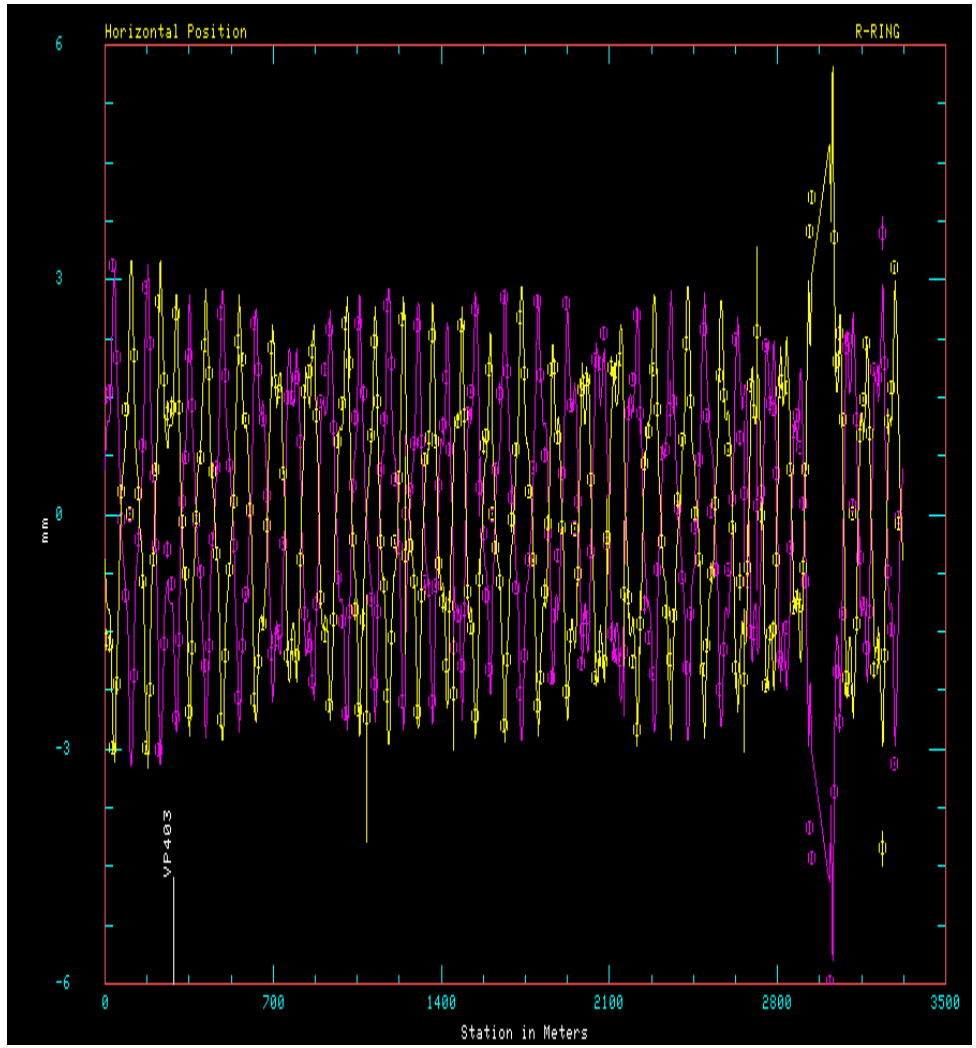
- All the BPM timing were adjusted to improve reliability.

- Although the absolute measurement of the Recycler beam position was not reliable enough, these work lead to a better measurement of the Recycler difference orbit.

- Recycler orbit has been stable for weeks for similar machine condition.

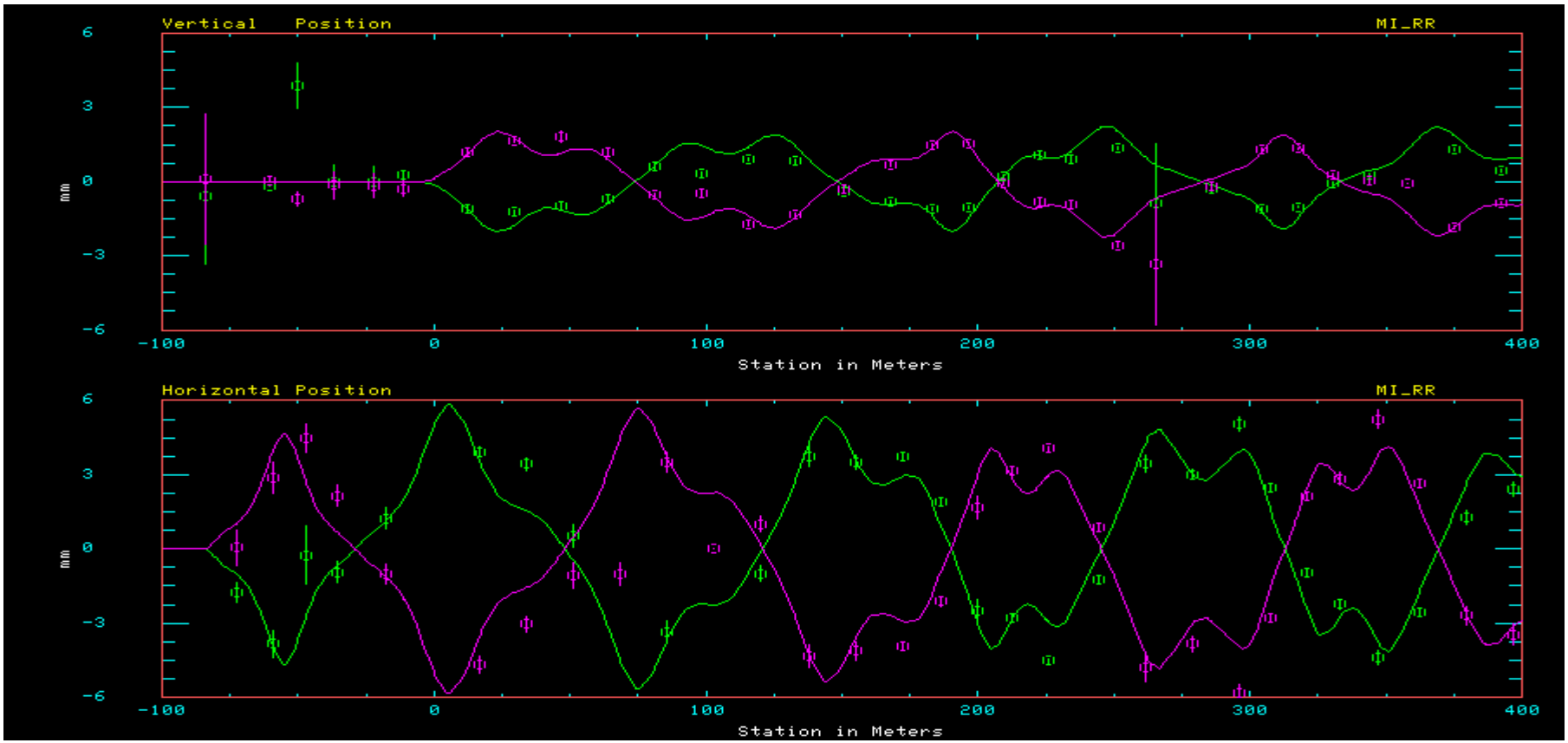
Horizontal BPM and Lattice





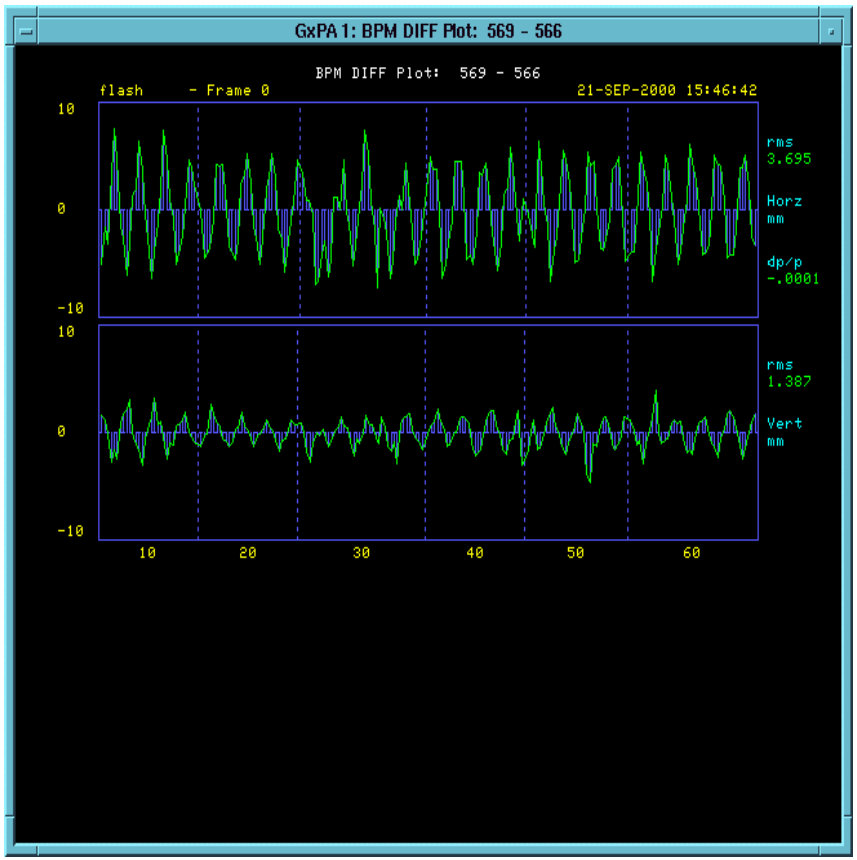
Injection Orbit Coupling

- The injection orbit is coupled. The coupling starts around the Lambertsons LAM321 & LAM328.
- No such coupling has been observed in the circulating beam.

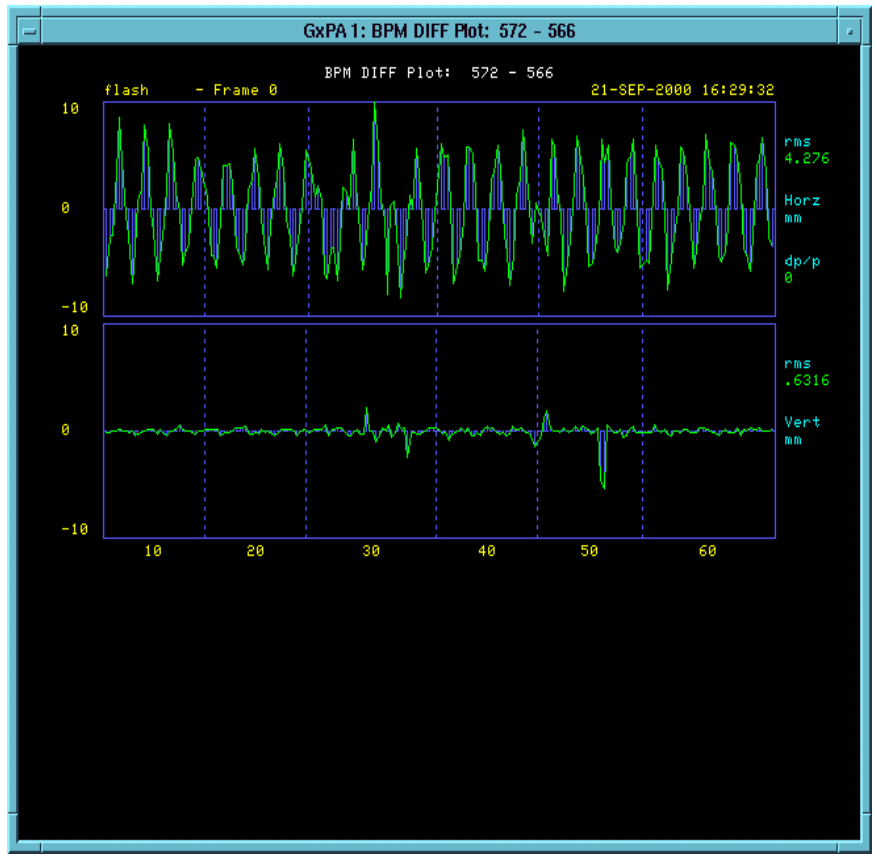


Decoupling the Injection orbit

We installed two skew quadrupoles in the RR30 transfer line to cancel the effect of skew quadrupole measured in LAM321 and 328.

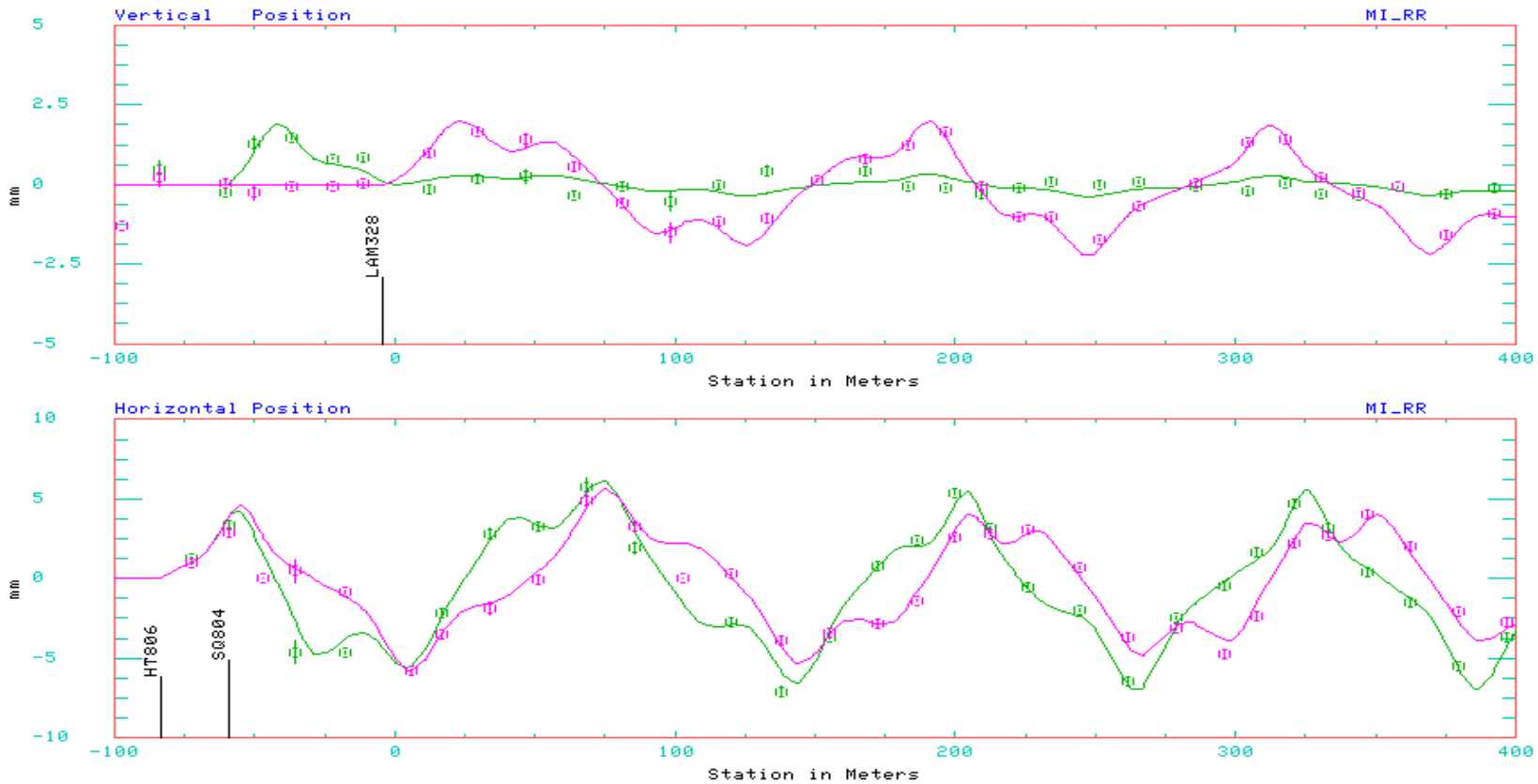


Coupled due to LAM321



Decoupled by SQ803

Decoupling of LAM328 Skew quadrupole effect by SQ804

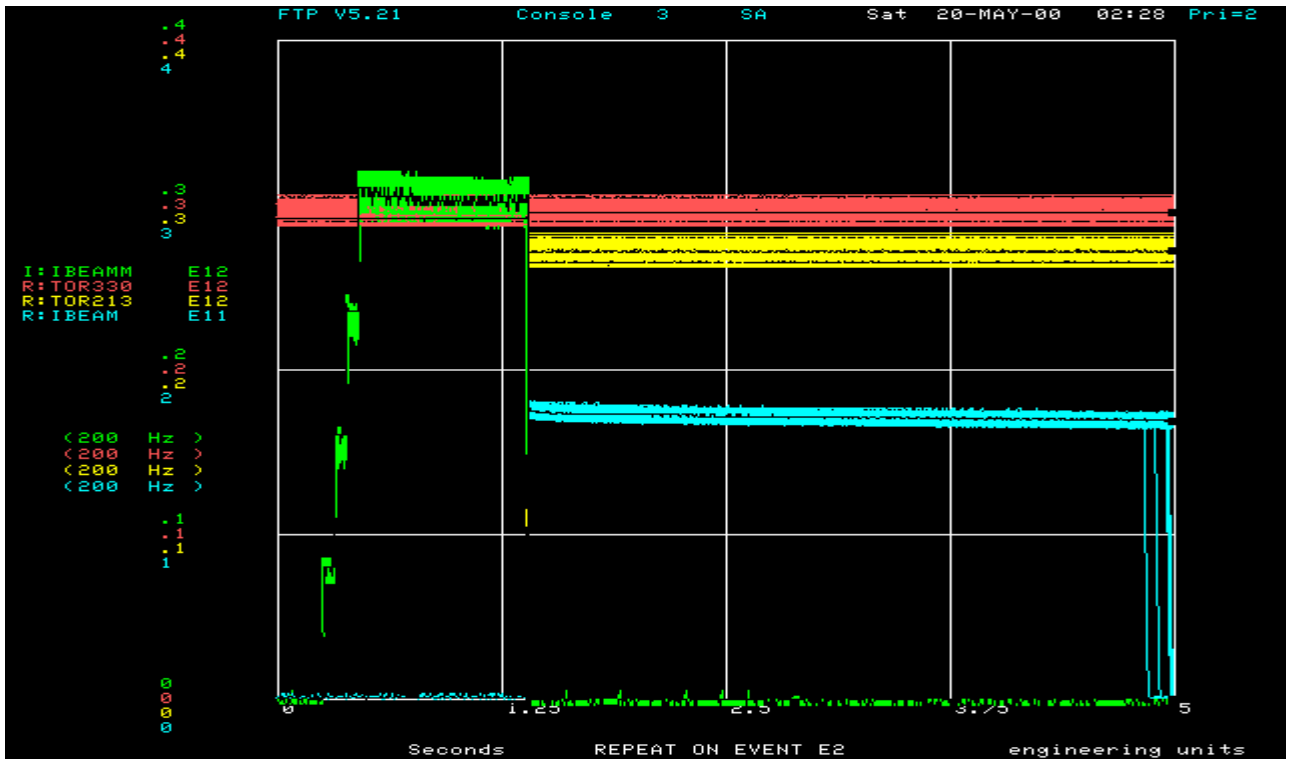


Orbit improvements

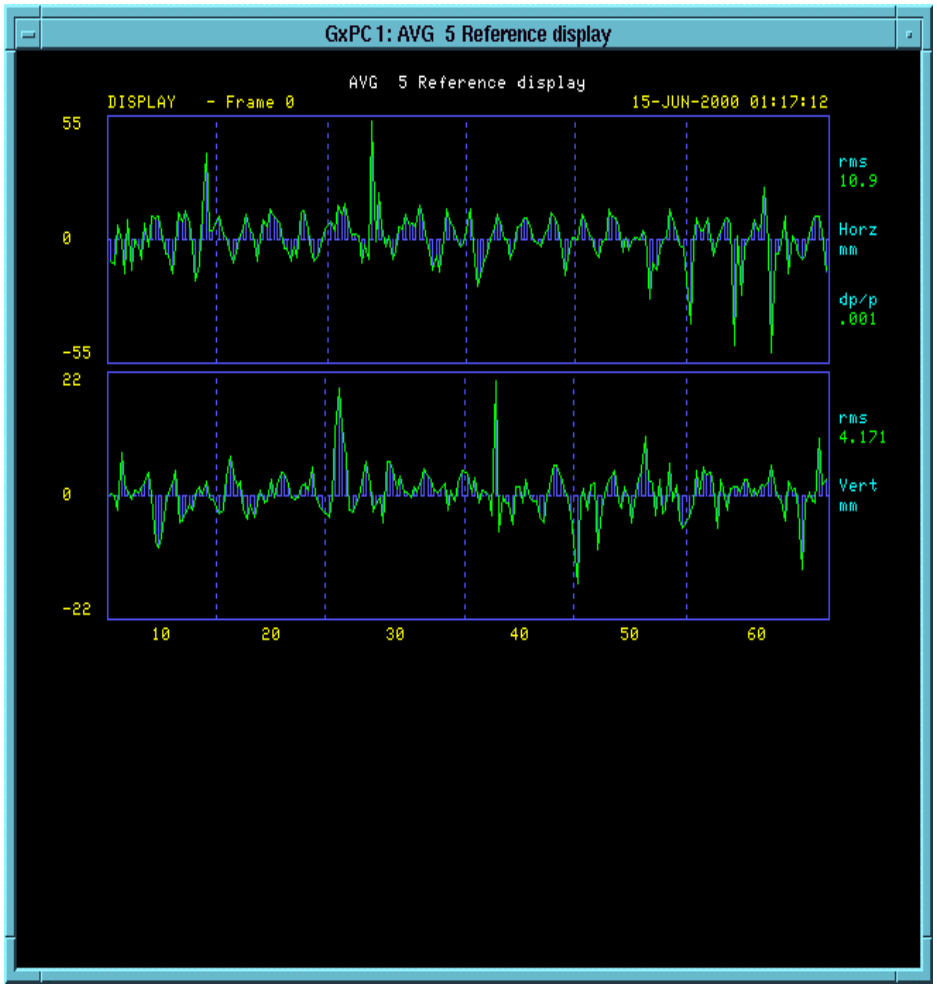
- Aided with semi-reliable BPM system we started to work on injection closure and reduction of closed orbit error.
- Recycler had only limited number of horizontal and vertical correctors which can be used for the closed orbit correction.
- The design of the Recycler required us to move magnets to reduce the closed orbit error. Calculations showed that we could reduce the closed orbit error sigma to 3 mm in both planes by about 12 magnet moves.
- Using the BPM data and a magnet move program we moved the Recycler magnets three times. Two times to correct the Horizontal orbit and one time to correct the vertical orbit.

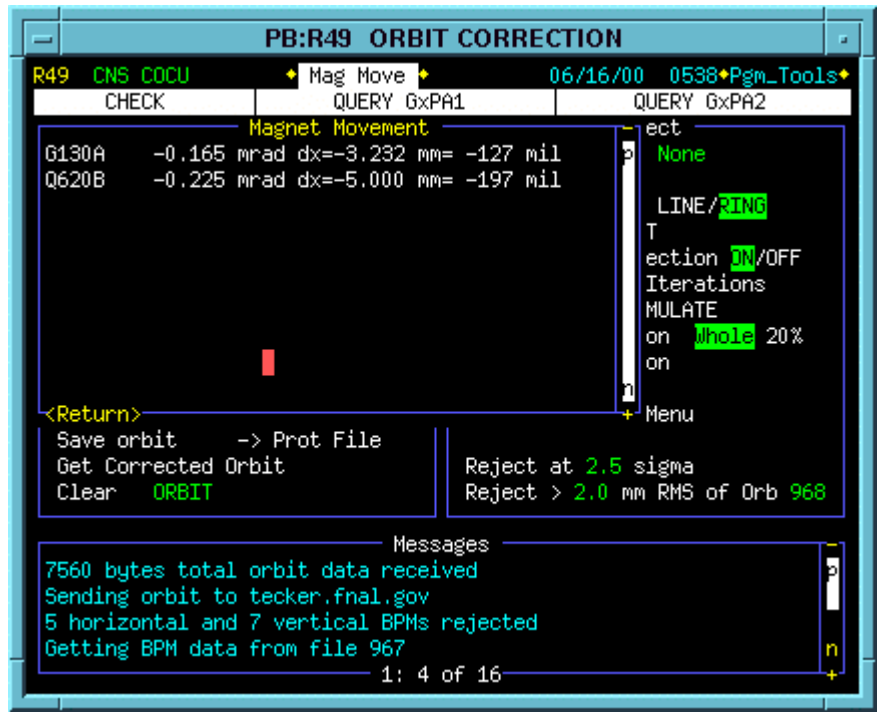
Efficiency Improvement using trims

• Before making a magnet move we studied the improvements of circulating beam efficiency by using the H &V correctors to reduce the orbit error. We could improve the circulating beam efficiency to about 60%.



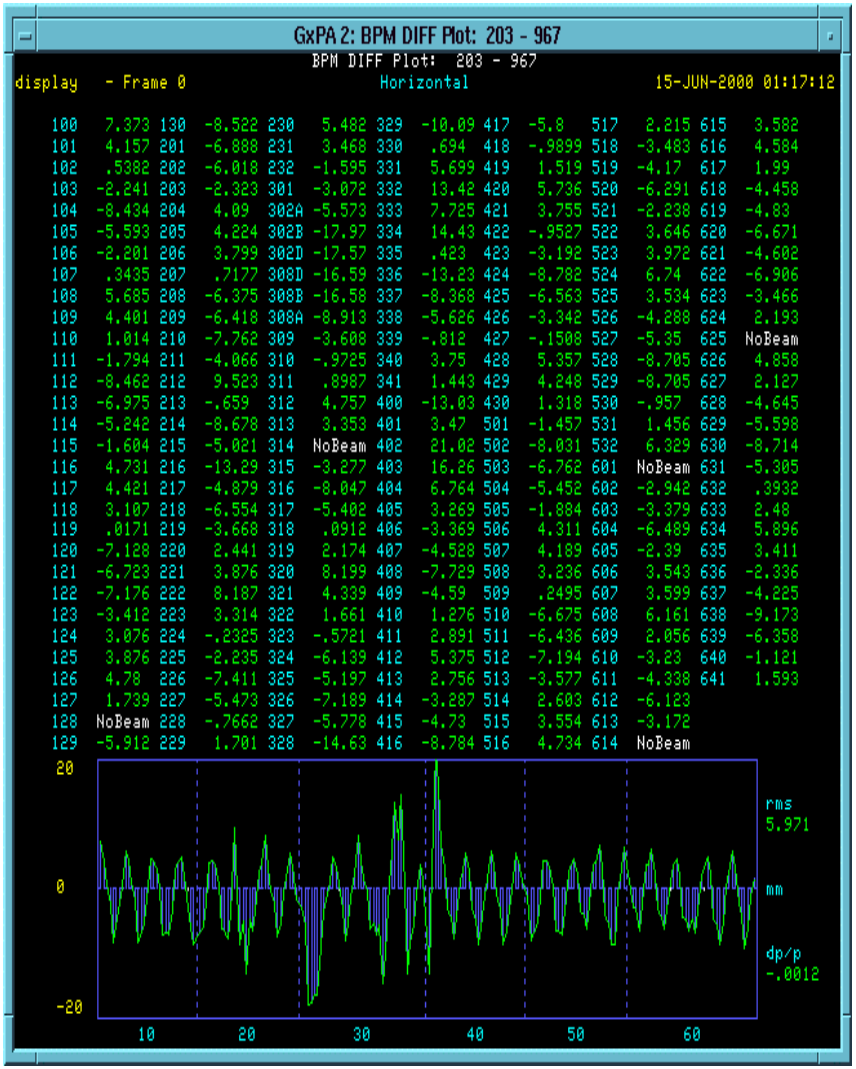
Horizontal Magnet Move



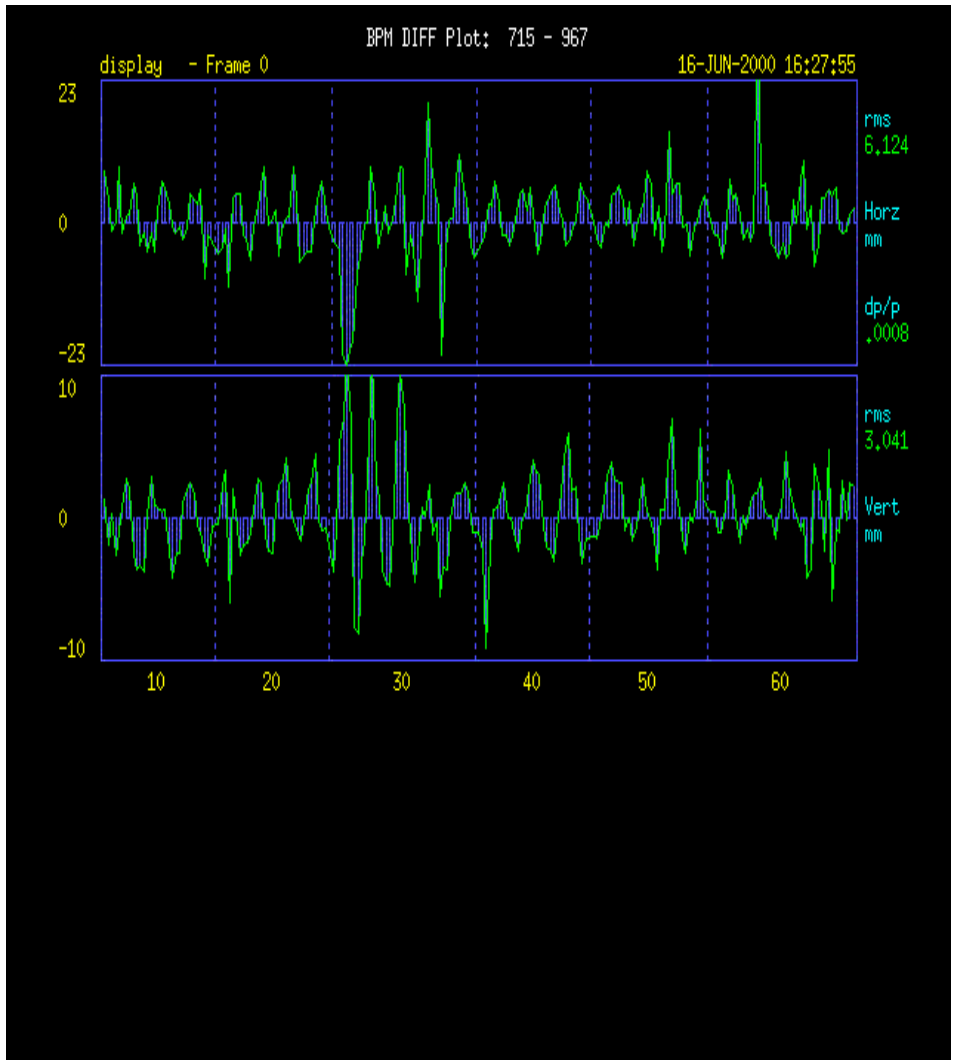


Horizontal Magnet Move...

Predicted Change



Actual Change



Recycler Alignment

- During Spring of 2000 all the Recycler Magnetic elements were aligned to the design specifications.

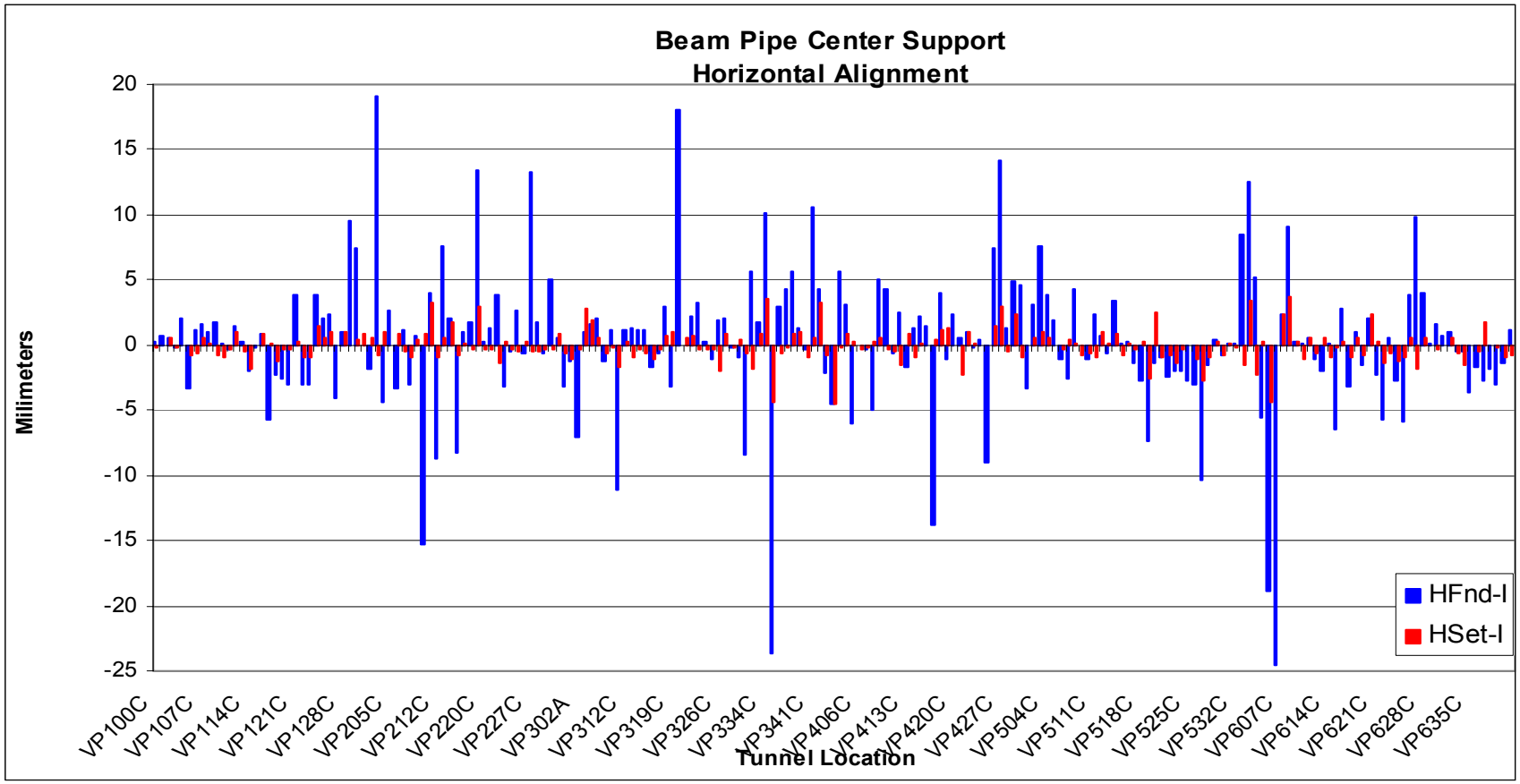
- Since early summer till Mid Oct 00 we have realigned all the other components of the Recycler.

  - The Beam pipes were aligned at the center support locations. Maximum misalignment found was about 25 mm (H) and 10 mm (V).

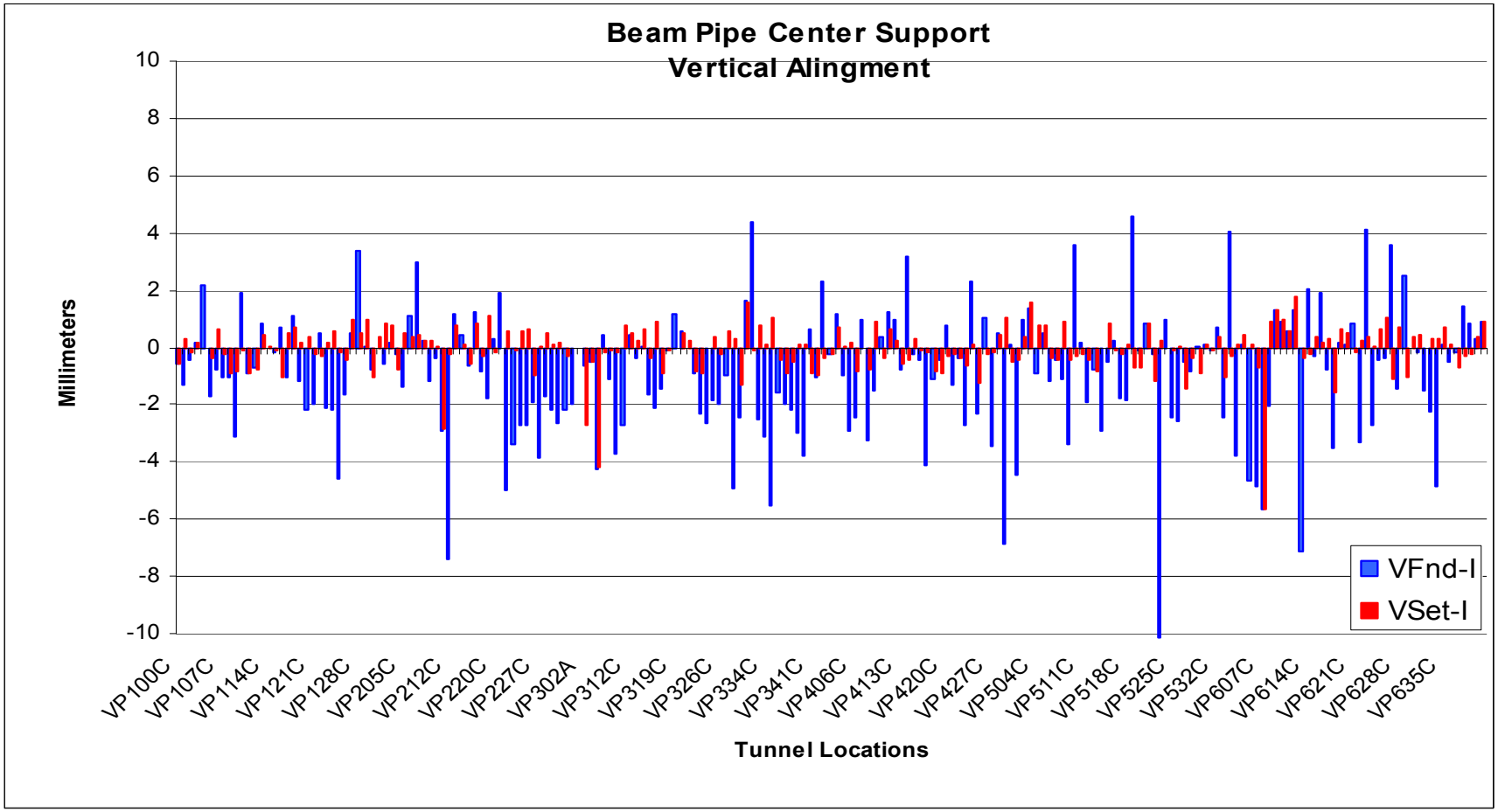
  - The Beam pipes were also aligned at the exit of magnets. Maximum misalignment found was about 12 mm (H) and 4 mm (V).

  - The BPM's were aligned. Maximum misalignment found was about 15 mm (H) and 8 mm (V).

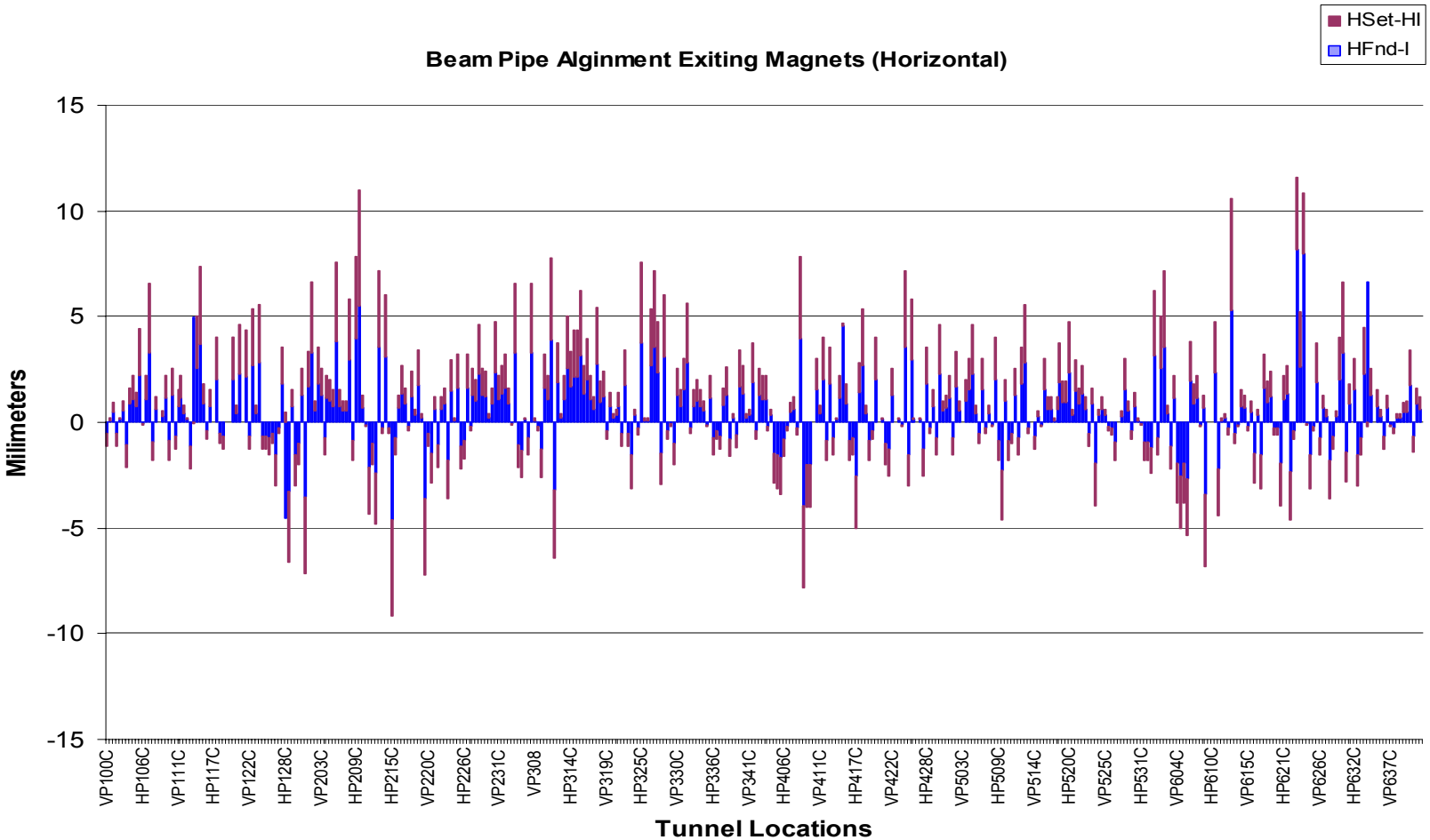
Alignment of Beam Pipe at the Center Support Horizontal



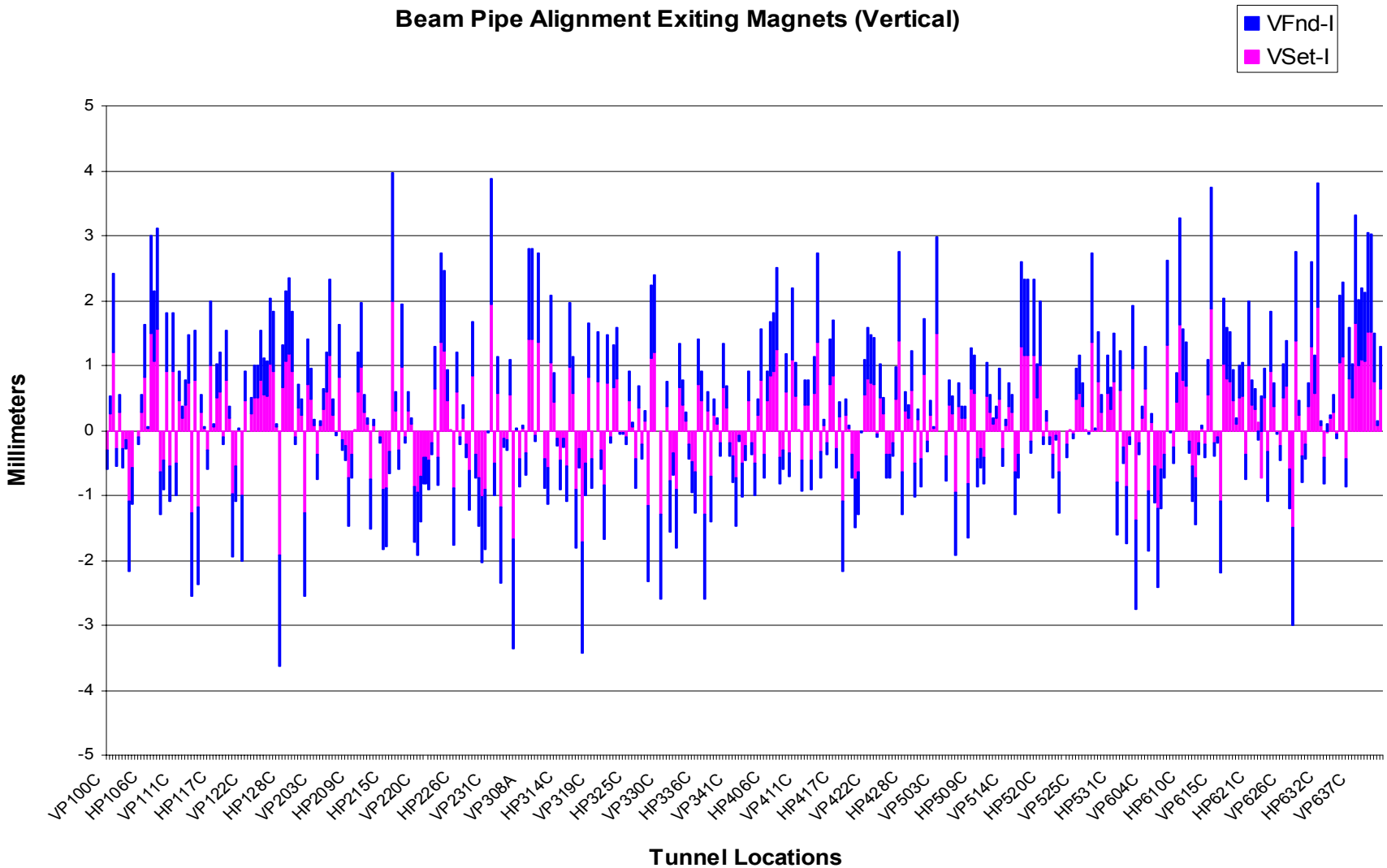
Alignment of Beam Pipe at the Center Support Vertical



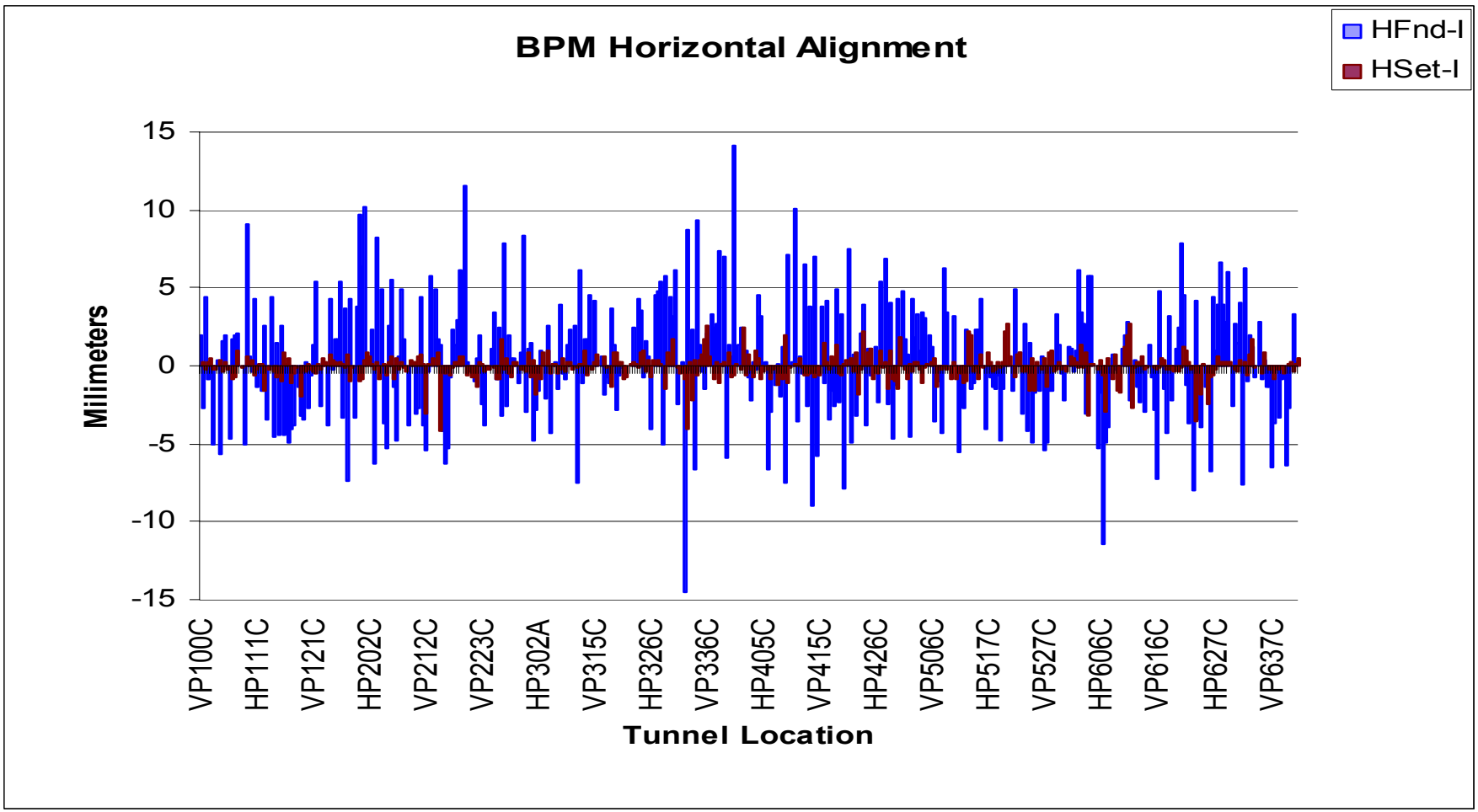
Alignment of Beam Pipe at the Exit of the Magnet Horizontal



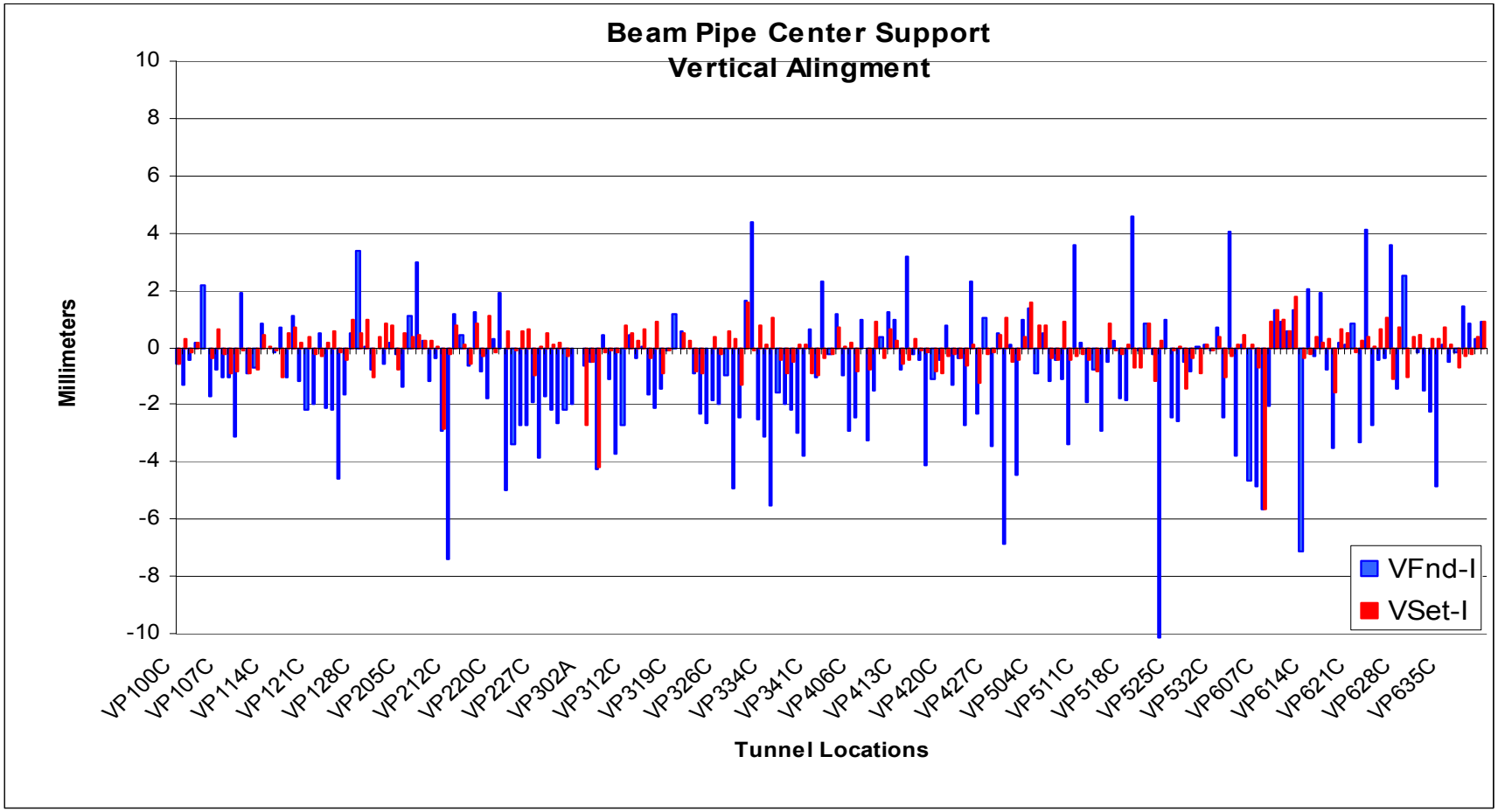
Alignment of Beam Pipe at the Exit of the Magnet Vertical



Alignment of the BPM Horizontal

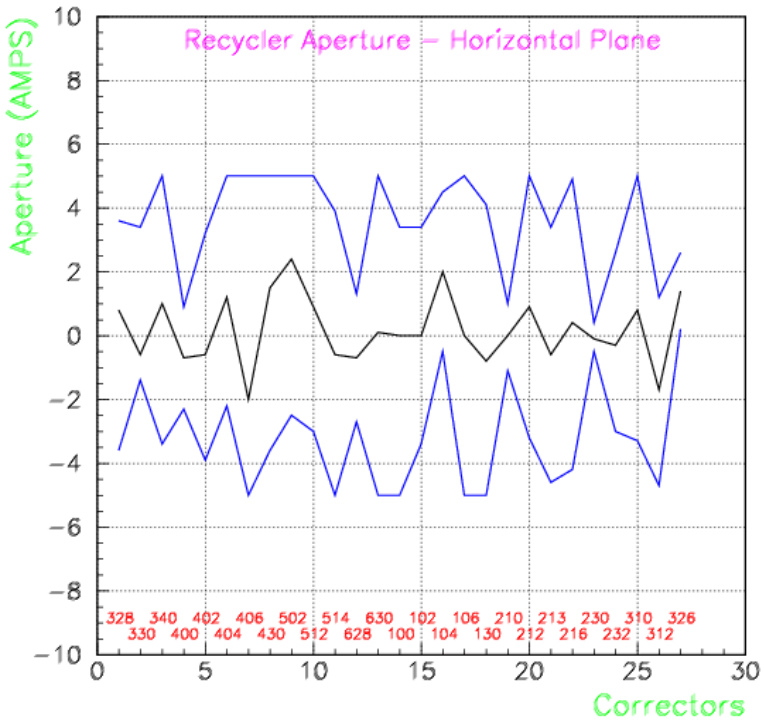


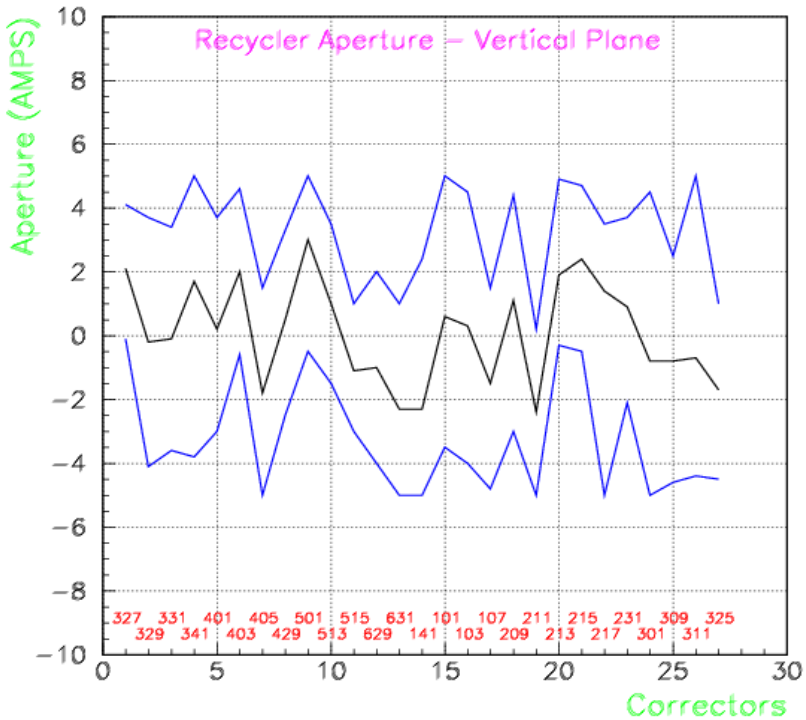
Alignment of the BPM Vertical



Aperture Scan of the Recycler

Aperture scan of the Recycler was performed after complete alignment by determining the 50% loss point of the beam or the maximum corrector current of 5 Amps in a three bump.





We have centered the beam in the Recycler based on these aperture scan results. This has helped improve the Recycler efficiency.

Shielding from MI Magnetic Field

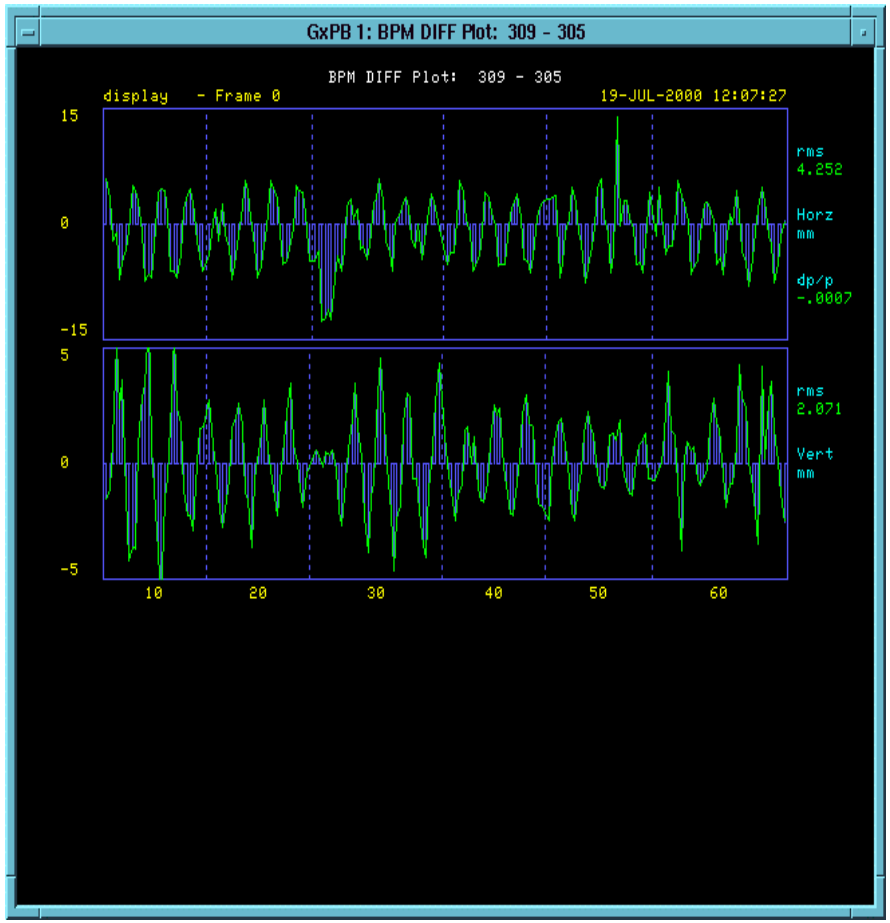
- Recycler Ring has been shielding from the MI field by placement of the Mu-Metal and soft-iron beam pipe around the Recycler pipe.

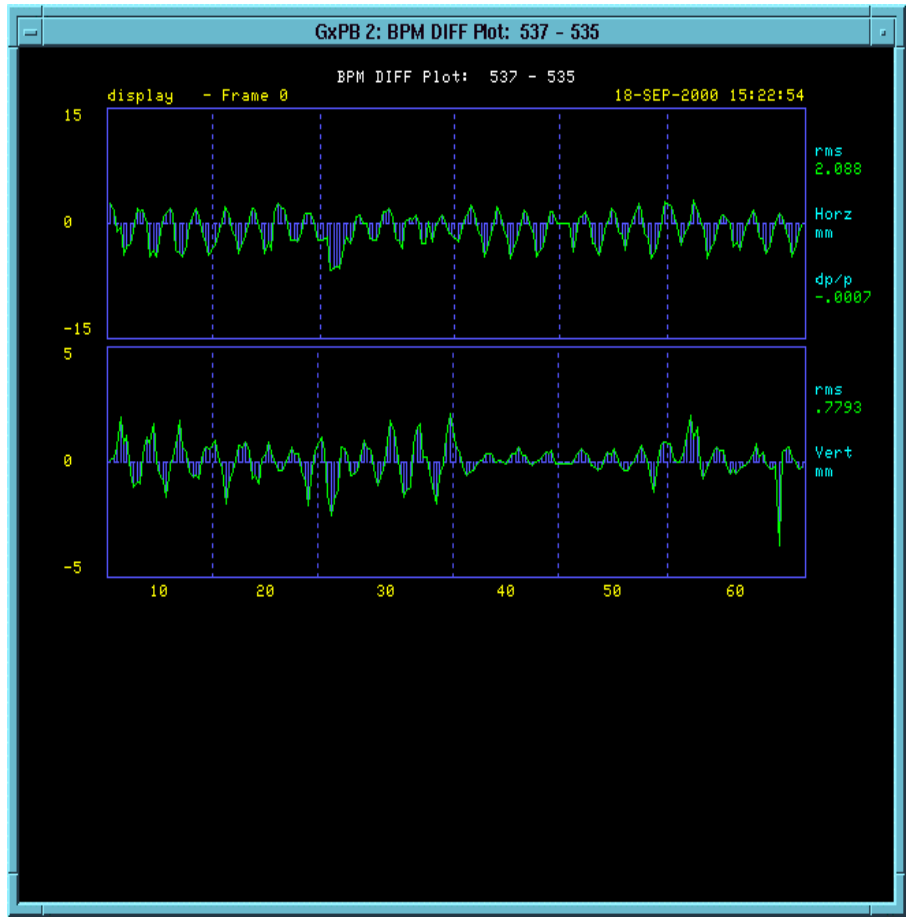
- The main problem location has been the MI30 High Beta insert region, where the MI Dipole bus has two expansion joints and busses also runs bare next to the tunnel wall. At other locations the busses are mostly behind the MI dipoles.

- We have made a power-on access to measure the magnetic field. Based on these and orbit measurements we have added additional shielding to this section and other expansion joints.

- A R&D of the shielding revealed that we needed a new mu-metal and rapping technique. We are installing this new shielding.

MI Magnetic Field effect on RR orbit

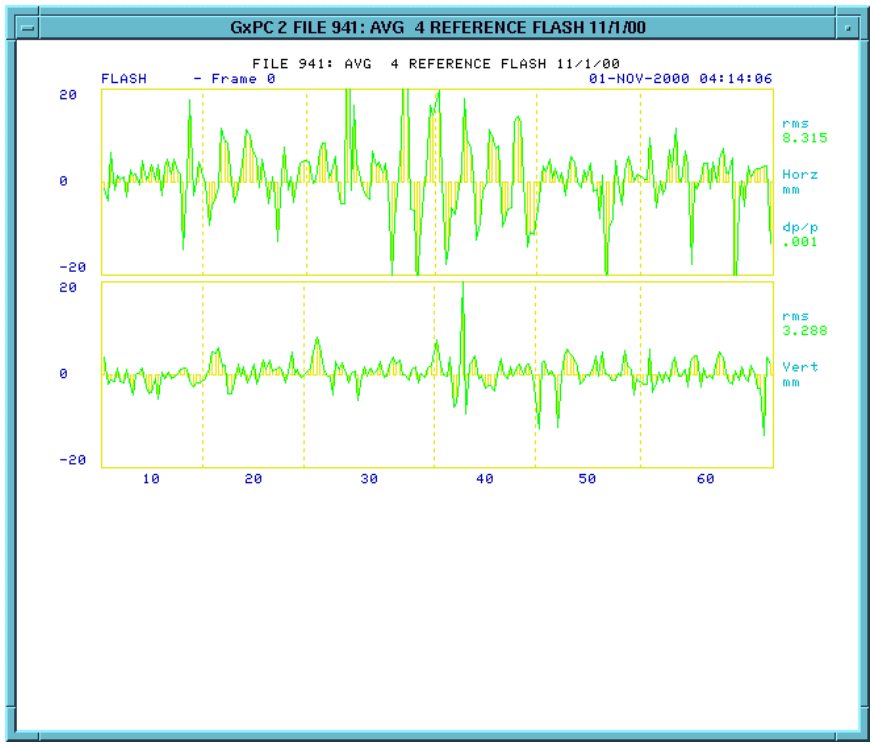




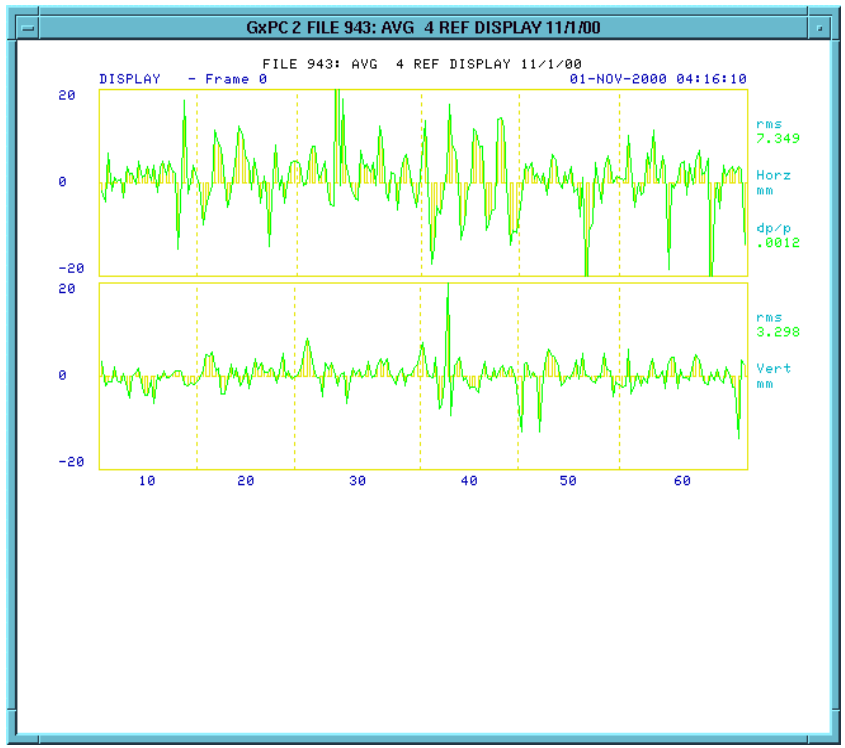
New shielding added in MI30 straight section reduces the effect by a factor of 2. The MI kick was not longer located at MI30 section of RR

The Recycler Orbit

Recycler orbits have improved after magnet moves, orbit smoothing and aperture centering using horizontal and vertical correctors .



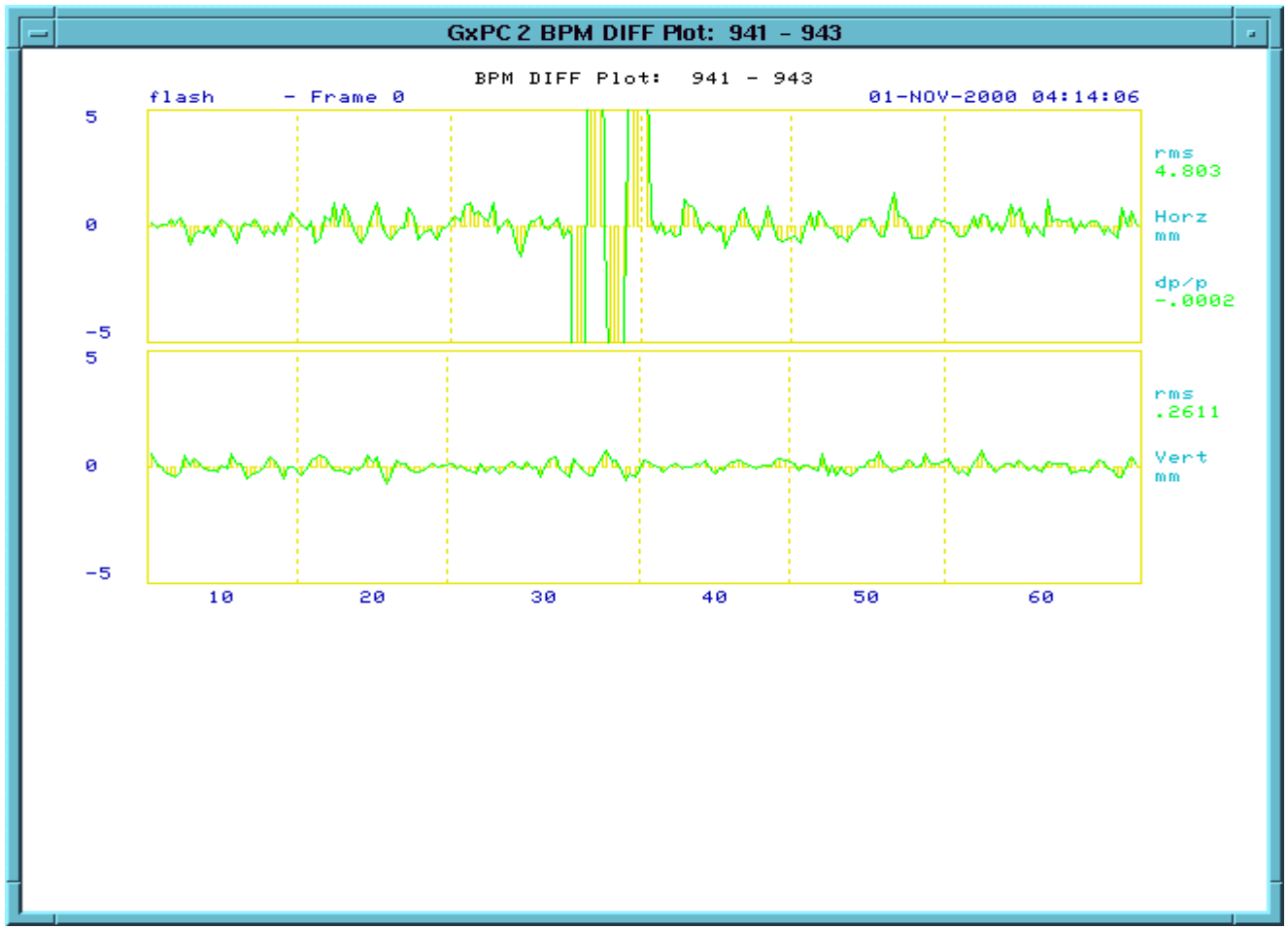
Injection



Closed

The Recycler Closure

- The RR Closure has improved considerably after implementation of a new software.

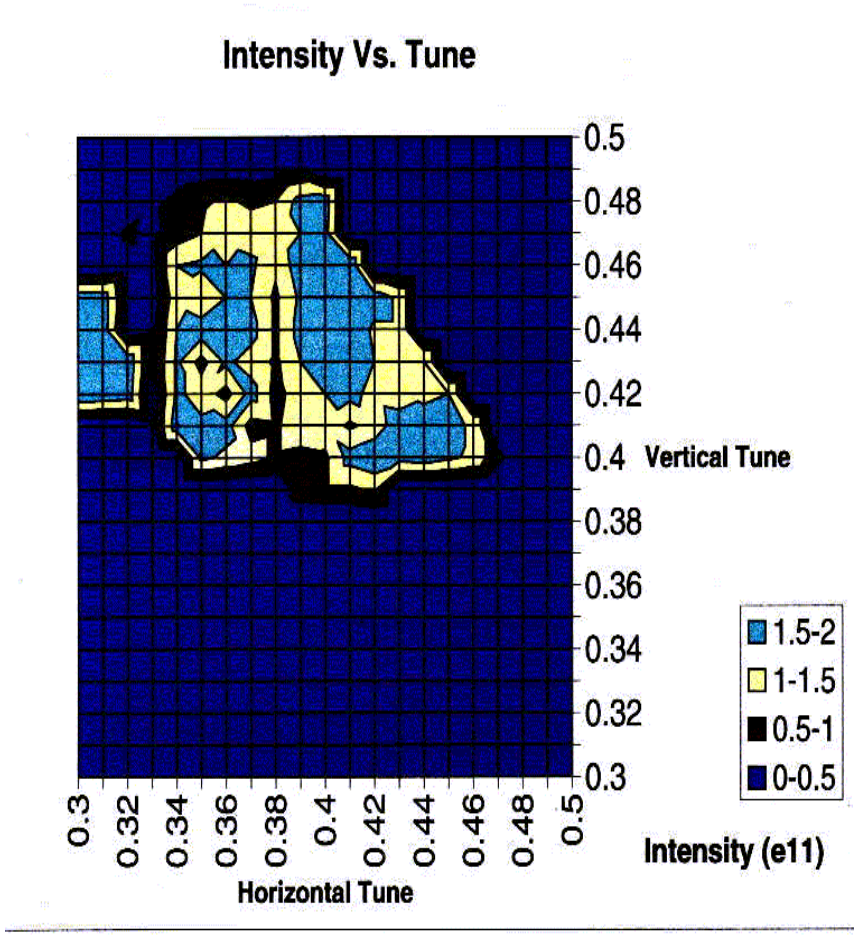


Horizontal

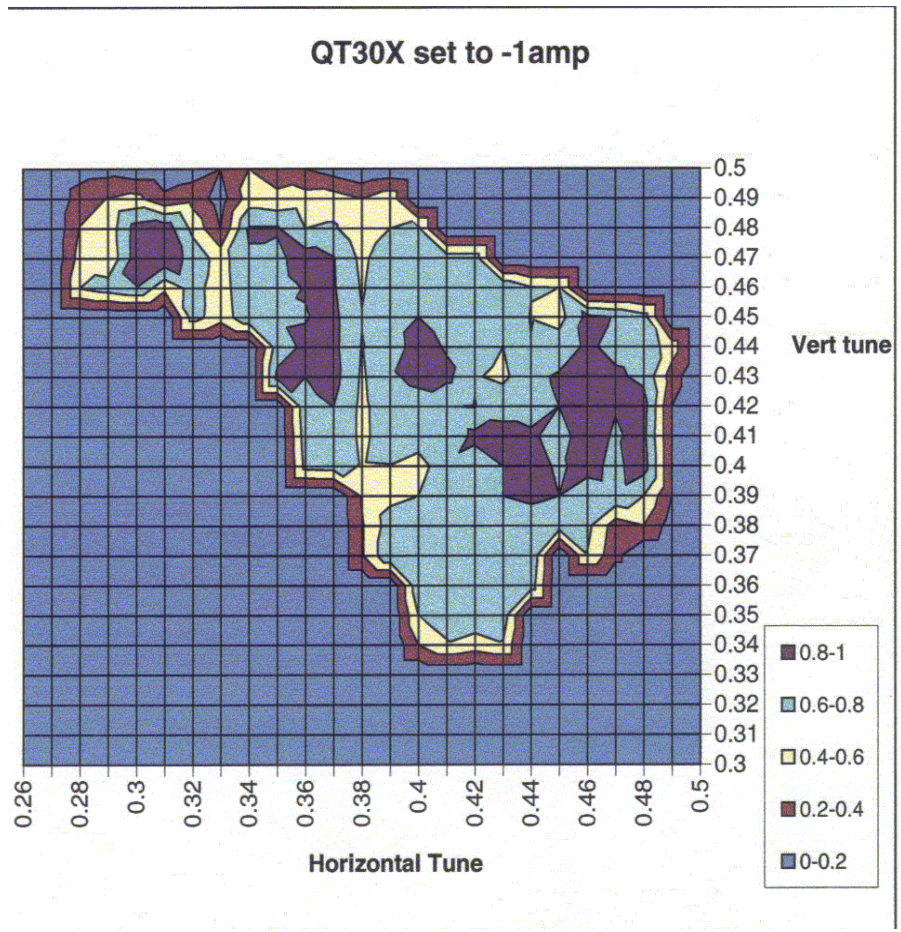
Vertical

Tune Scan of the Recycler

March 00

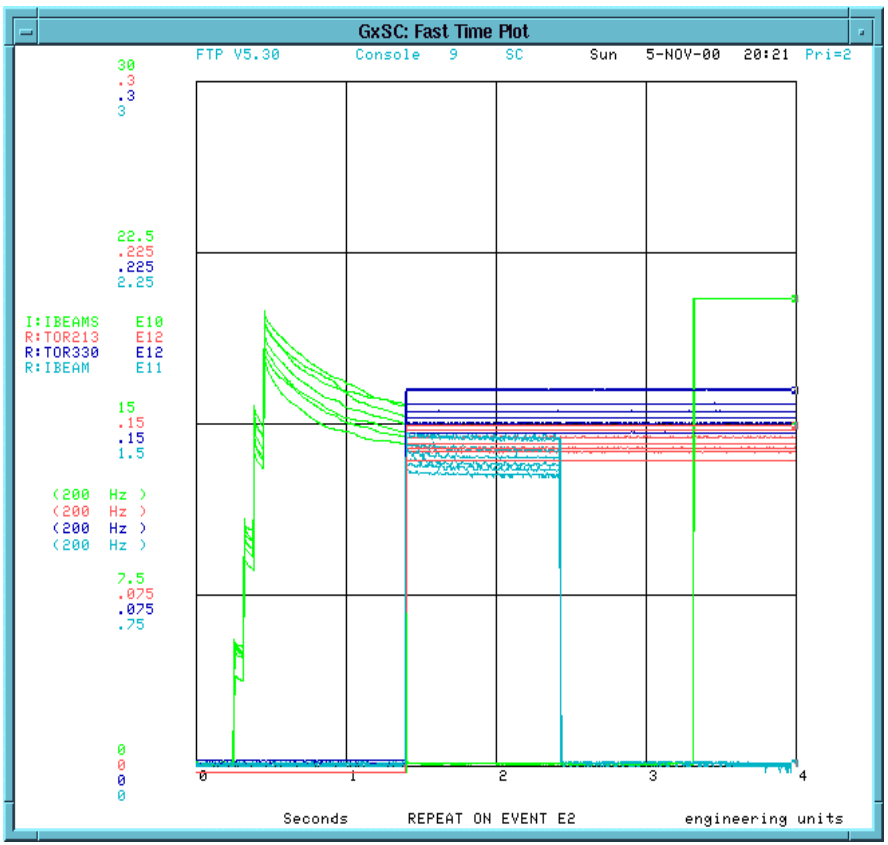


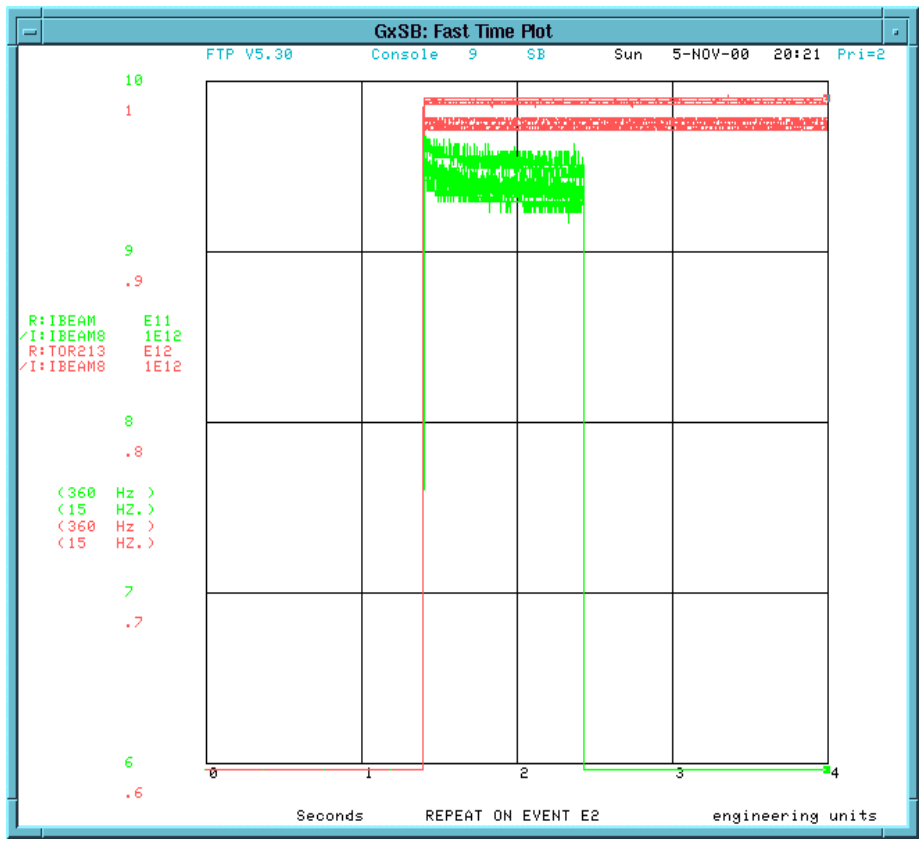
November 00



The Recycler Efficiency

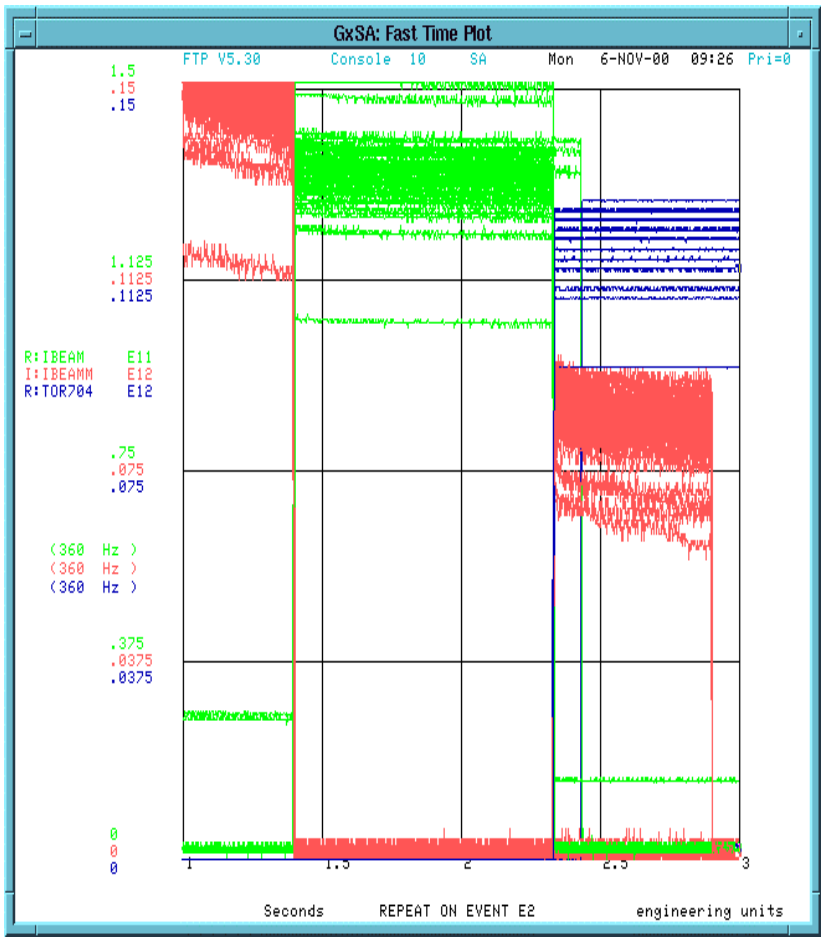
The Recycler circulating beam efficiency has improved to > 90% after alignment and aperture scan. Machine operating point is close to its design.



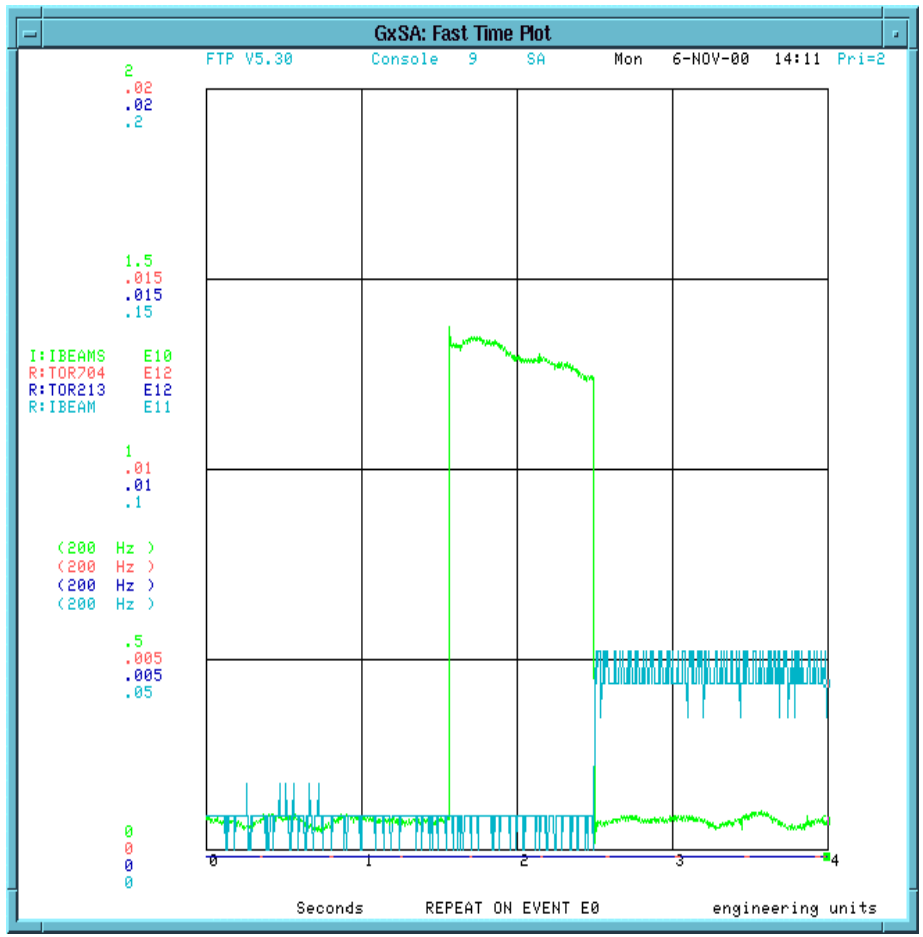


Other Recycler Commissioning

- Commissioning of the RR20 beam line.



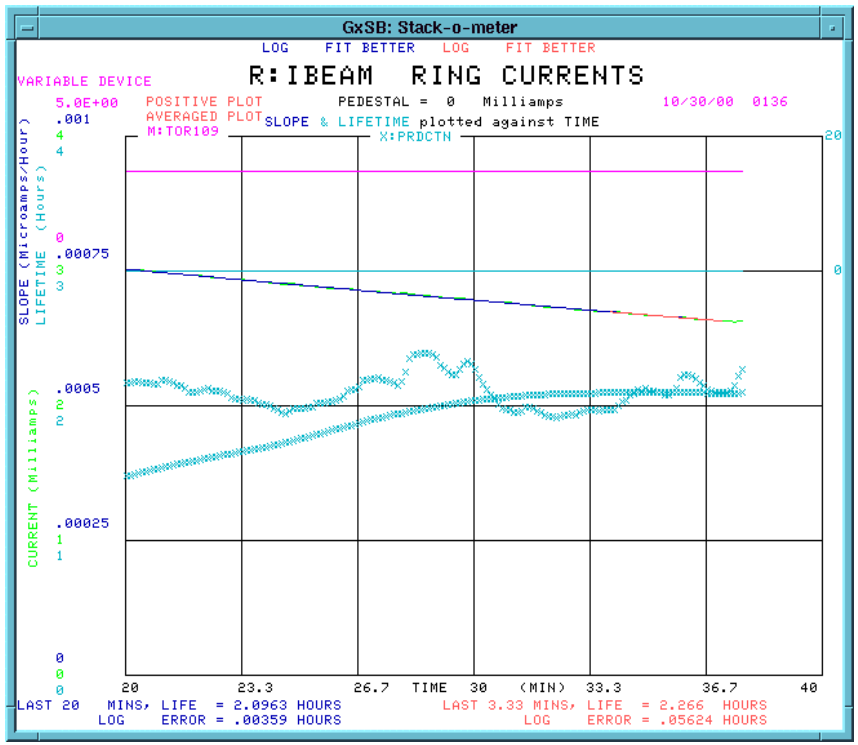
- Antiproton transfer in RR

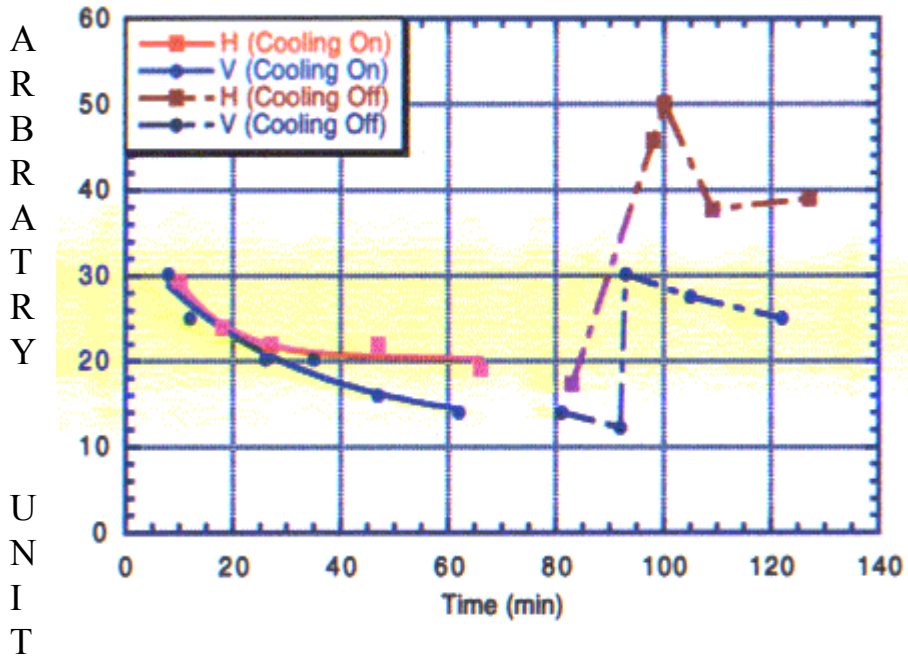


The Recycler Cooling

- At present the RR ring has only the proton cooling tanks installed.

The commissioning and installation of pbar tanks will be discussed by Ralph in detail.





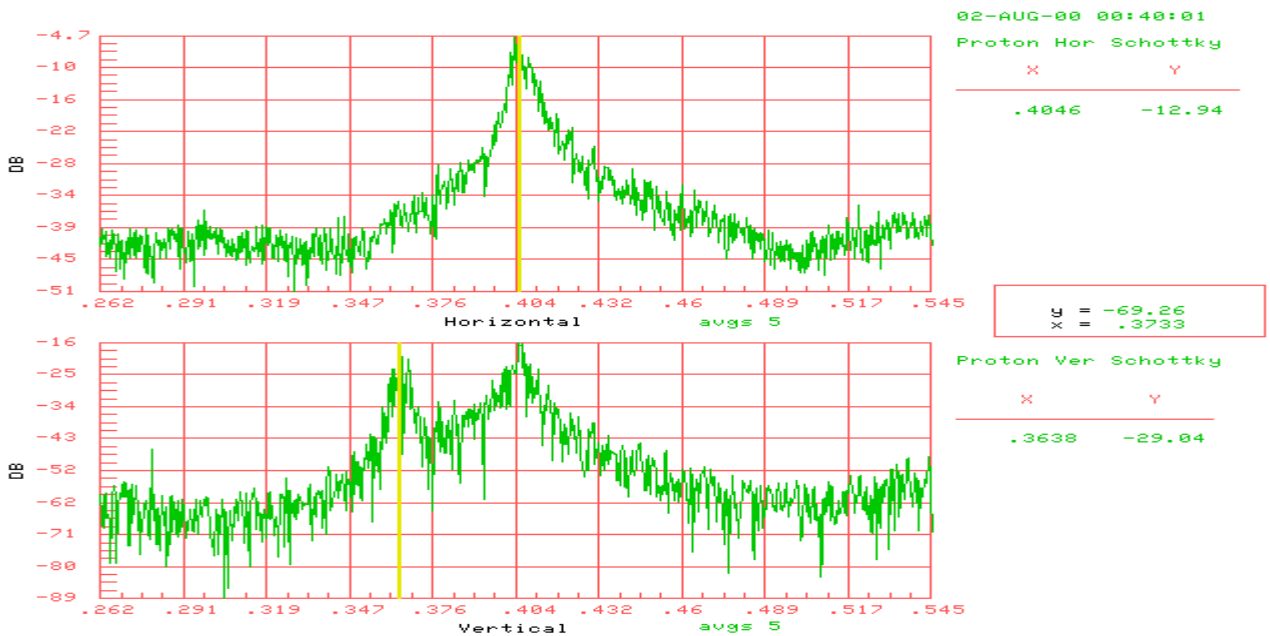
Lifetime without cooling is about 1 hour and with cooling about 2 hours. We have measured better lifetime.

Understanding the Recycler Lattice

- We have constructed a detailed lattice of the Recycler (V20). This includes all the measured magnetic properties of each magnet installed in the tunnel.

- The Recycler Fractional tune is lower than calculated by as build lattice.

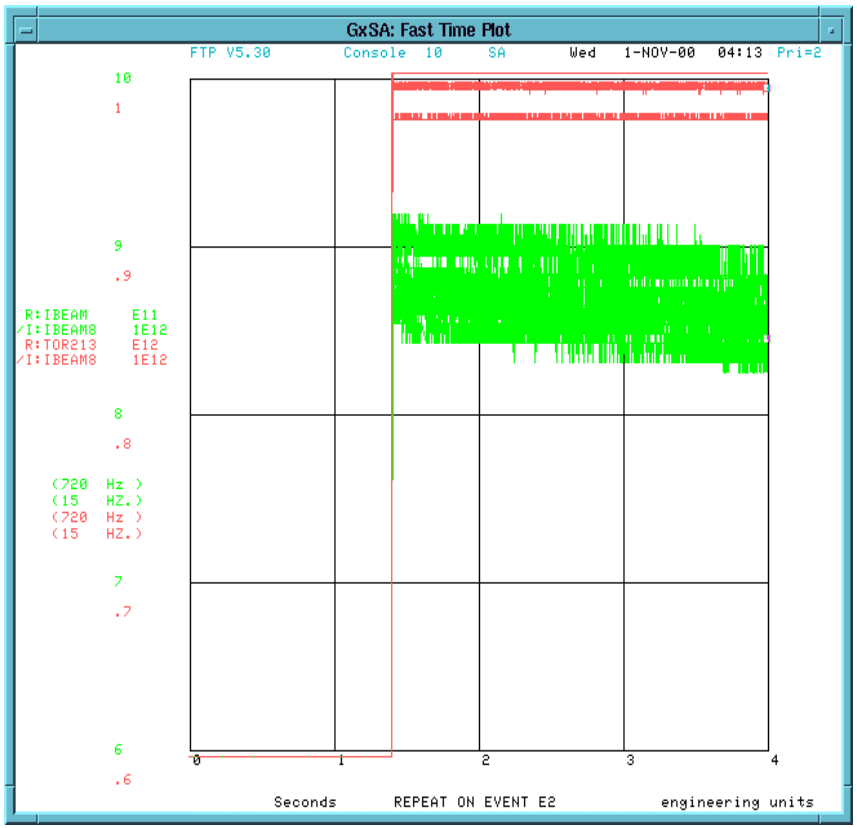
Calculation



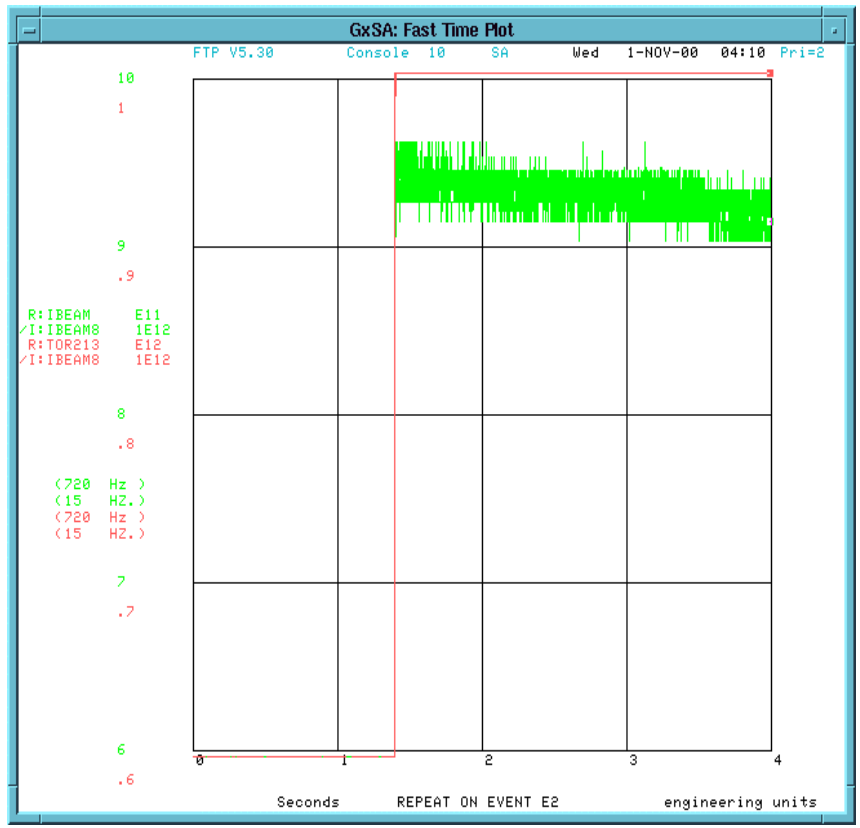
.415

.390

Recycler Circulating beam Efficiency improves if we turn on the two trim quadrupoles qt302/307 placed around high beta insert to -1 Amp.

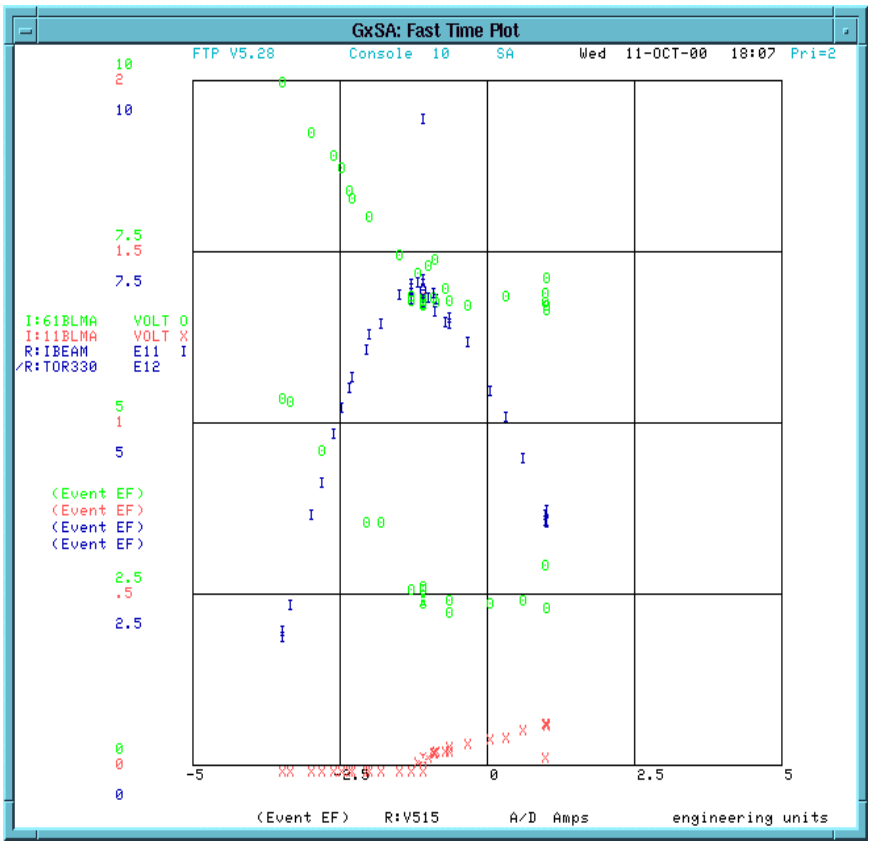


Qt 302/307 off

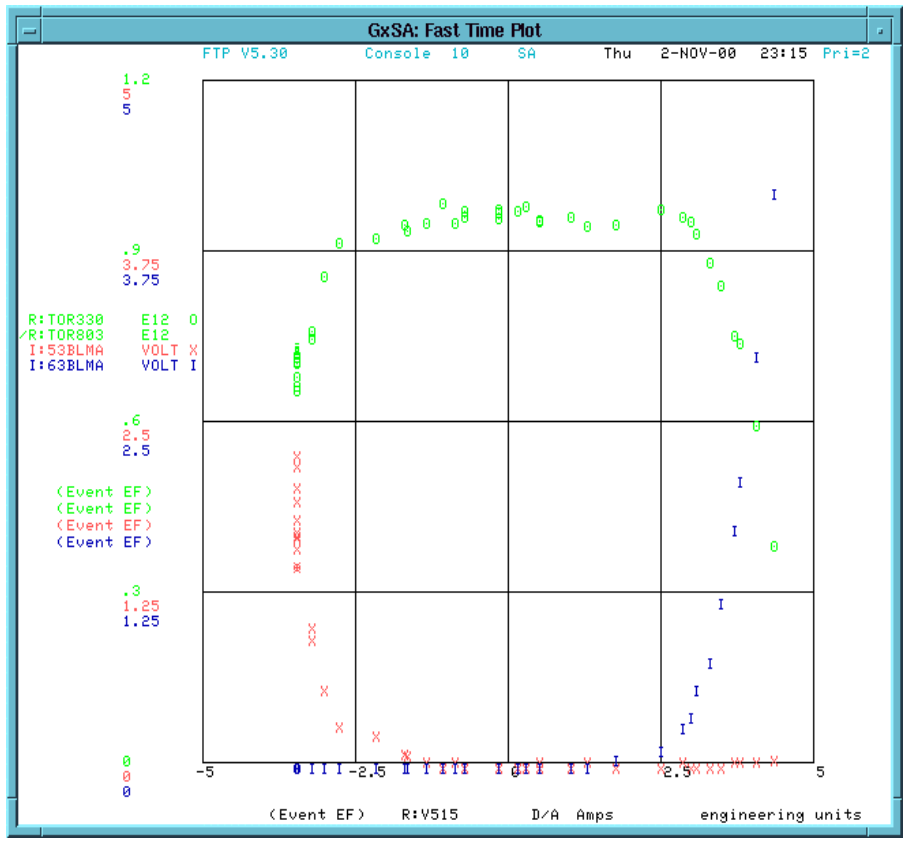


Qt 302/307 on

- Recycler three bumps are not closed across high beta insert.
- For tight aperture locations the single turn aperture scan aperture is considerably larger than the circulating beam aperture.

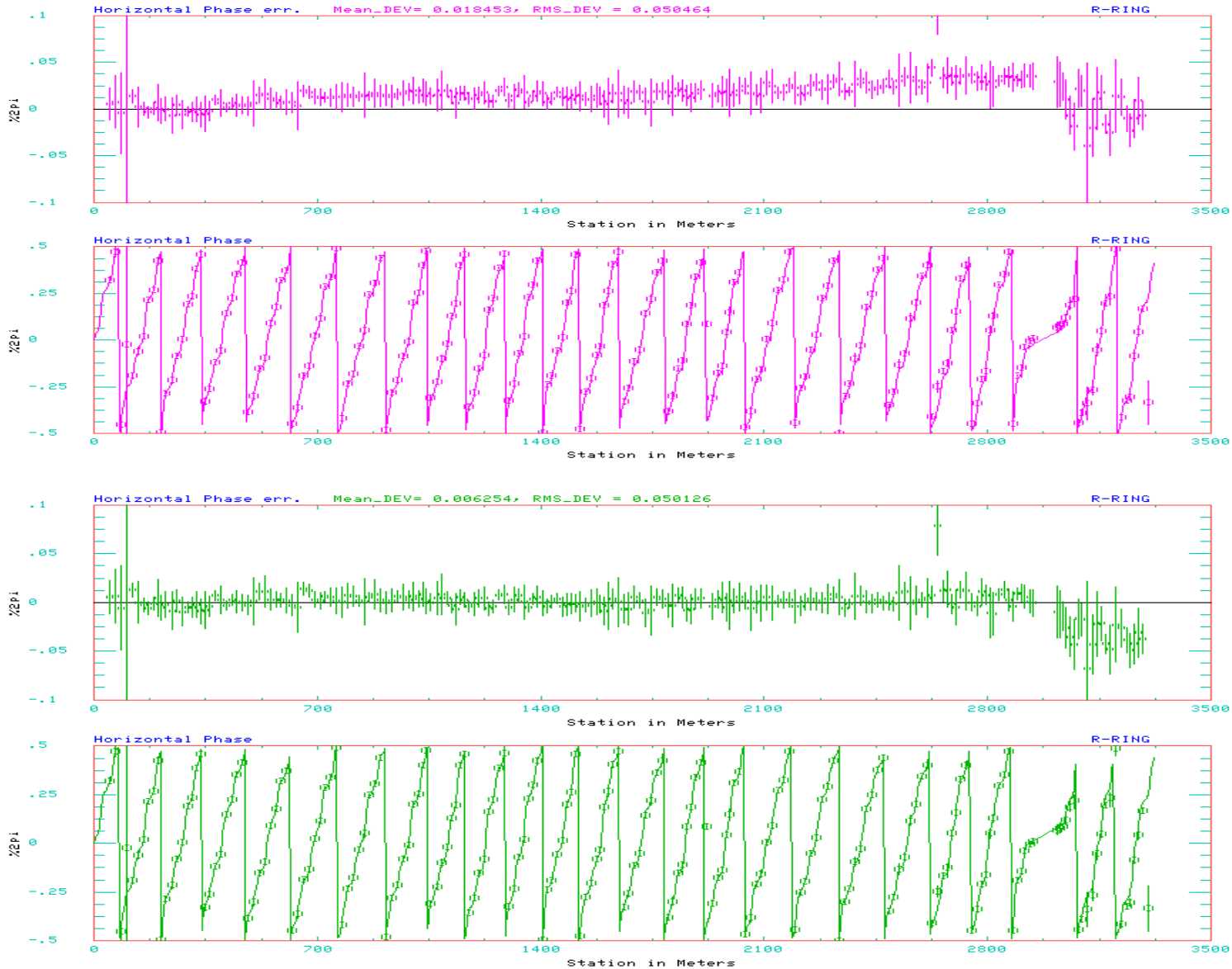


Circulating



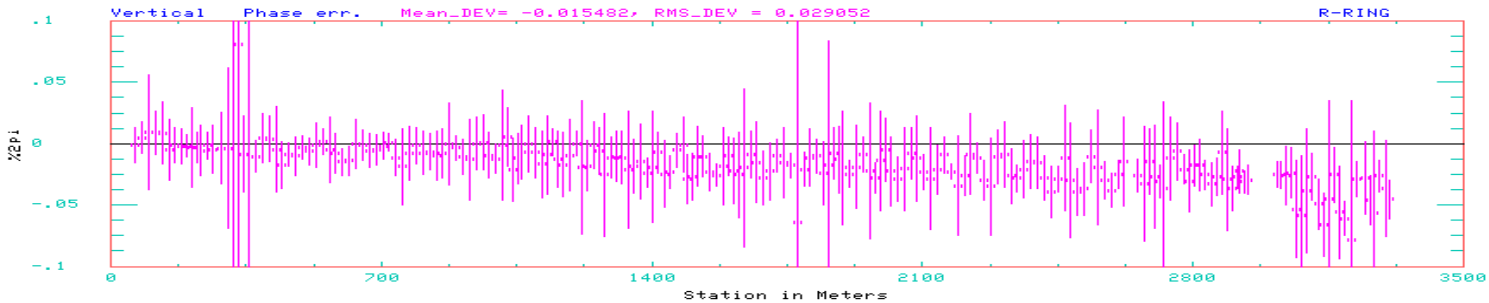
1.5 turns

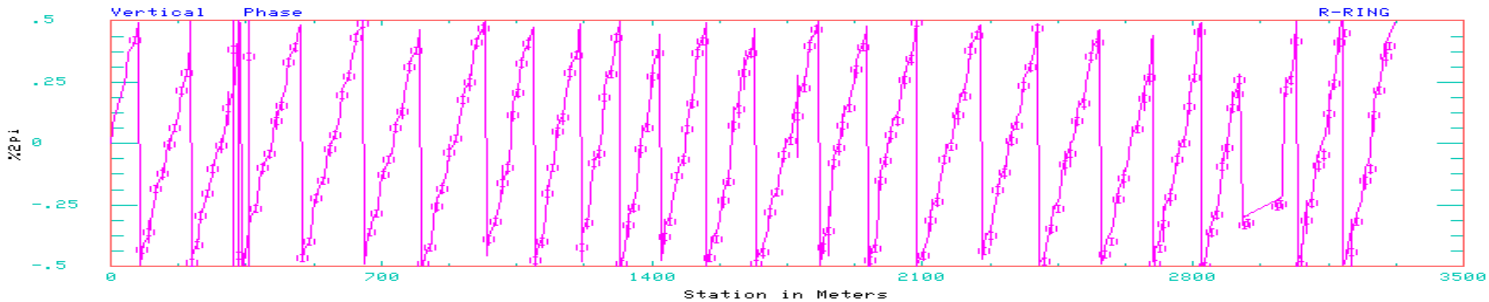
Horizontal Phase advance error by analysis of the single kick injection orbit data

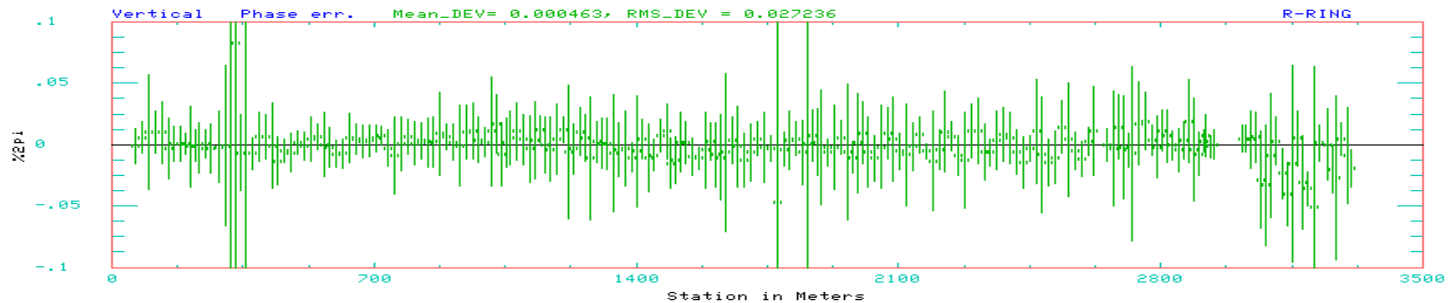


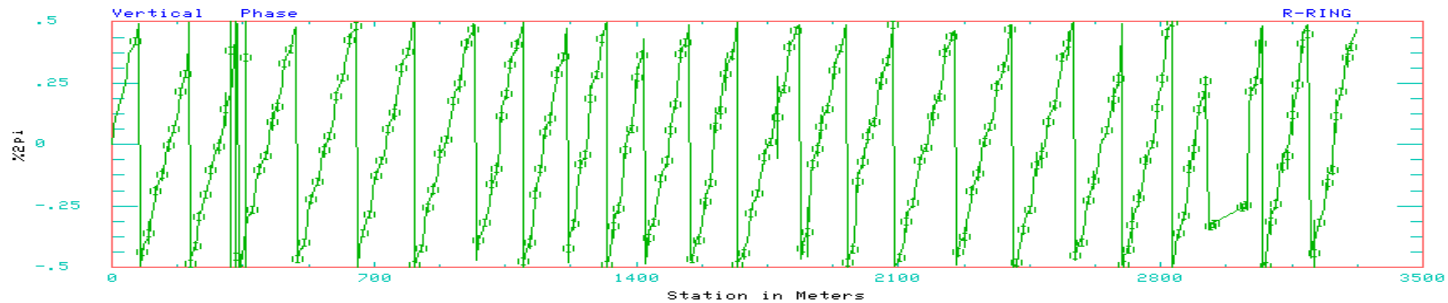
Qruadrupole error of 0.6 Units in CFM

Vertical Phase advance error by analysis of the single kick injection orbit data.







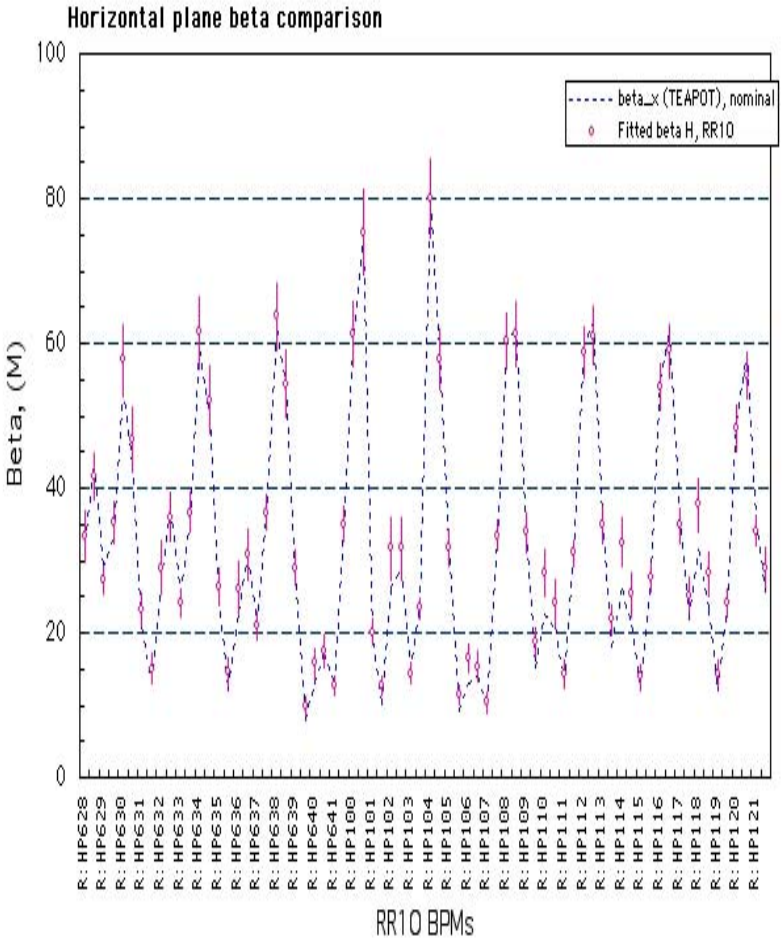


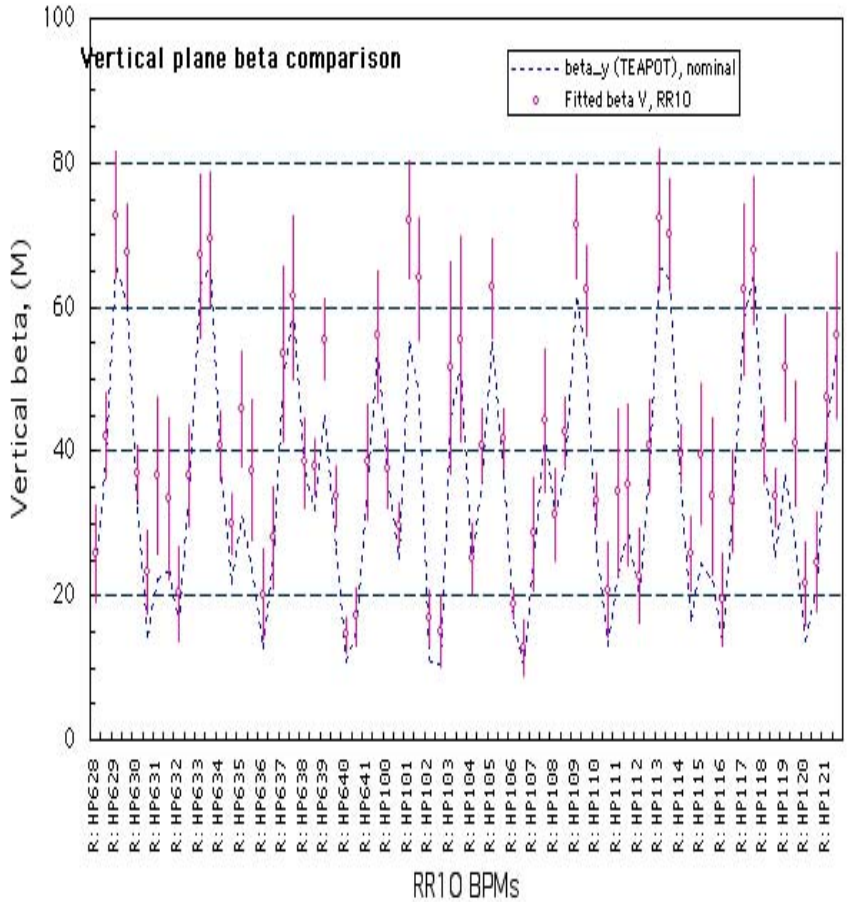
Quad error in CFM 0.4 unit.

Measured beta at the trim quadrupole locations

Location	Plane	Slope	*4pi	*1/k1	*1/L	Num Quad	Beta (m)	Beta Mad	%Error
qt601	Horizontal	0.00231	12.57	335.961	3.281	2	16.00069	12.1	32%
	vertical	0.011107				2	76.95156	57.8	33%
qt602	Horizontal	0.0107				2	74.13178	52.5	41%
	vertical	0.001762				2	12.2068	9.4	30%
qt603	Horizontal	0.000673				2	4.660603	7	-33%
	vertical	0.005354				2	37.0936	39.1	-5%
qt604	Horizontal	0.0075				2	51.96153	48.2	8%
	vertical	0.001305				2	9.041306	9.1	-1%
qt605	Horizontal	0.00192				2	13.30215	12.1	10%
	vertical	0.00987				2	68.3786	58	18%
qt606	Horizontal	0.0102				2	70.66768	50.1	41%
	vertical	0.002486				2	17.22144	8.8	96%
qt607	Horizontal	0.000862				2	5.973012	7	-15%
	vertical	0.005404				2	37.43655	39.4	-5%
qt608	Horizontal	0.0078				2	54.03999	50.6	7%
	vertical	0.0013				2	9.006665	9.7	-7%
qt609	Horizontal	0.002163				2	14.98363	12.1	24%
	vertical	0.01008				2	69.83629	57.3	22%
qt302	Horizontal	0.0139				1	192.6041	182	6%
	vertical	0.01227				1	170.0181	184	-8%
qt307	Horizontal	0.0117				1	162.12	178	-9%
	vertical	0.014				1	193.9897	185	5%

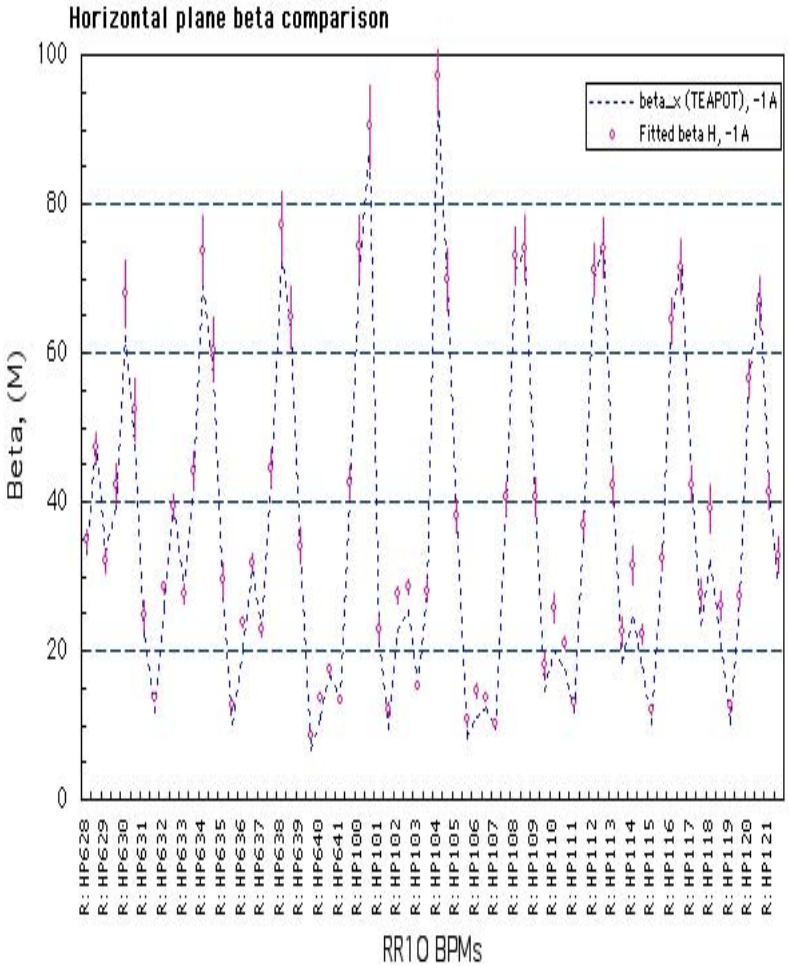
Recycler beta function measurement using Turn by Turn BPM data

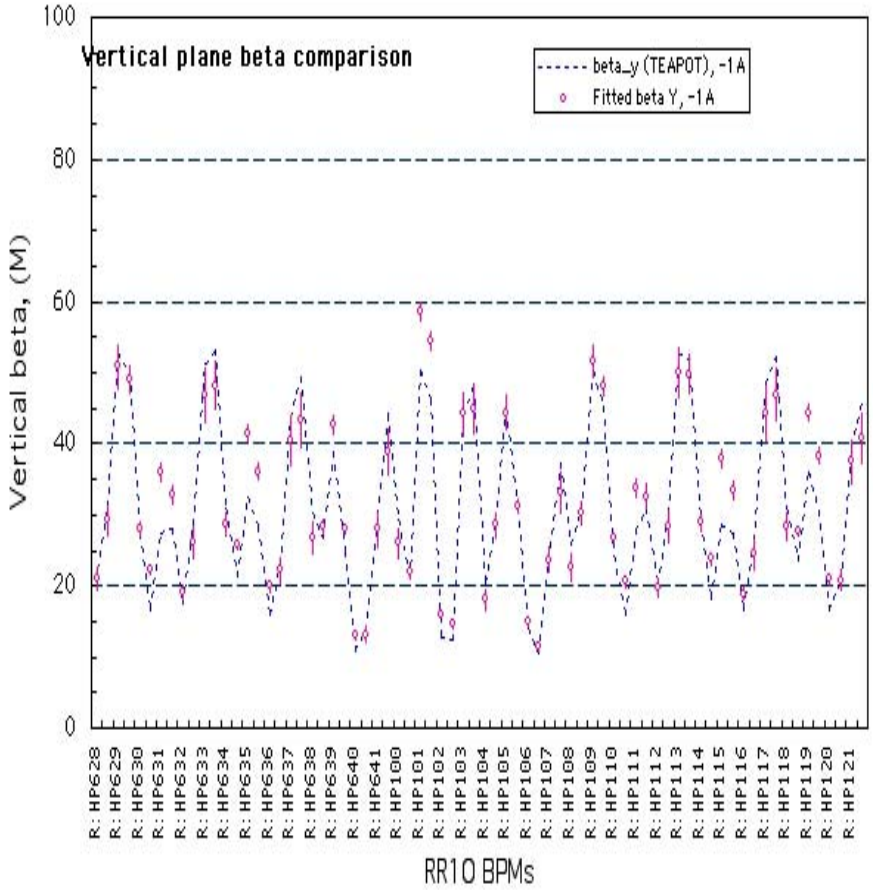




Qt302 and 307 trim quads are off. TEAPOT calculations assumes that all High beta quadrupoles are weak by 1%.

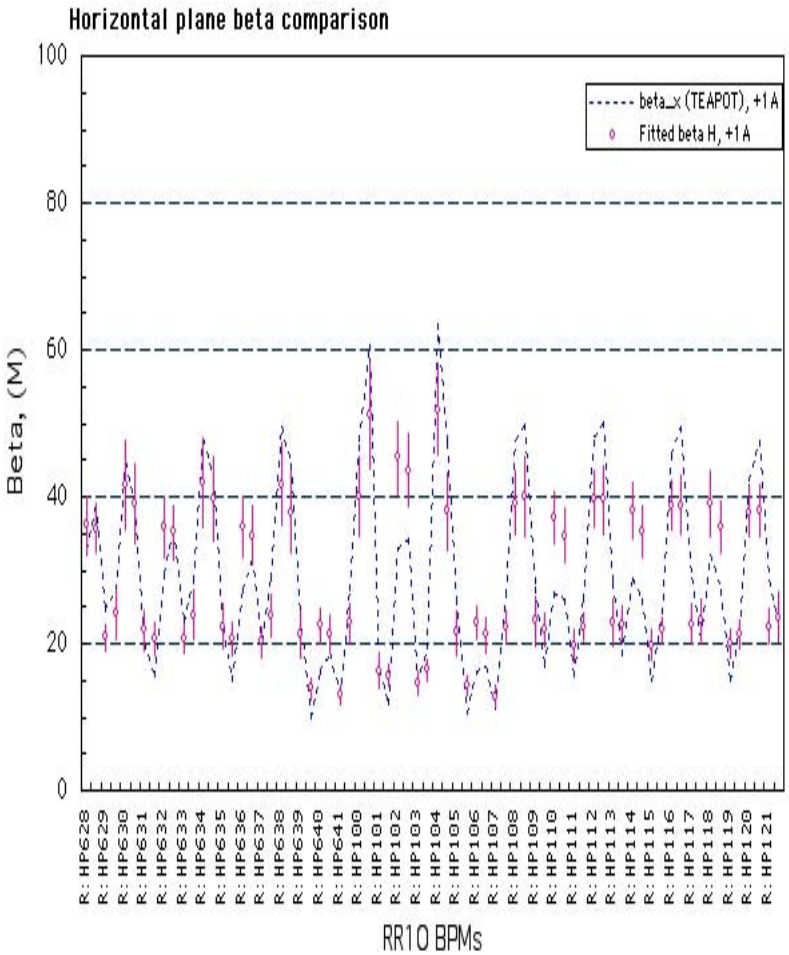
TBT Beta function ….

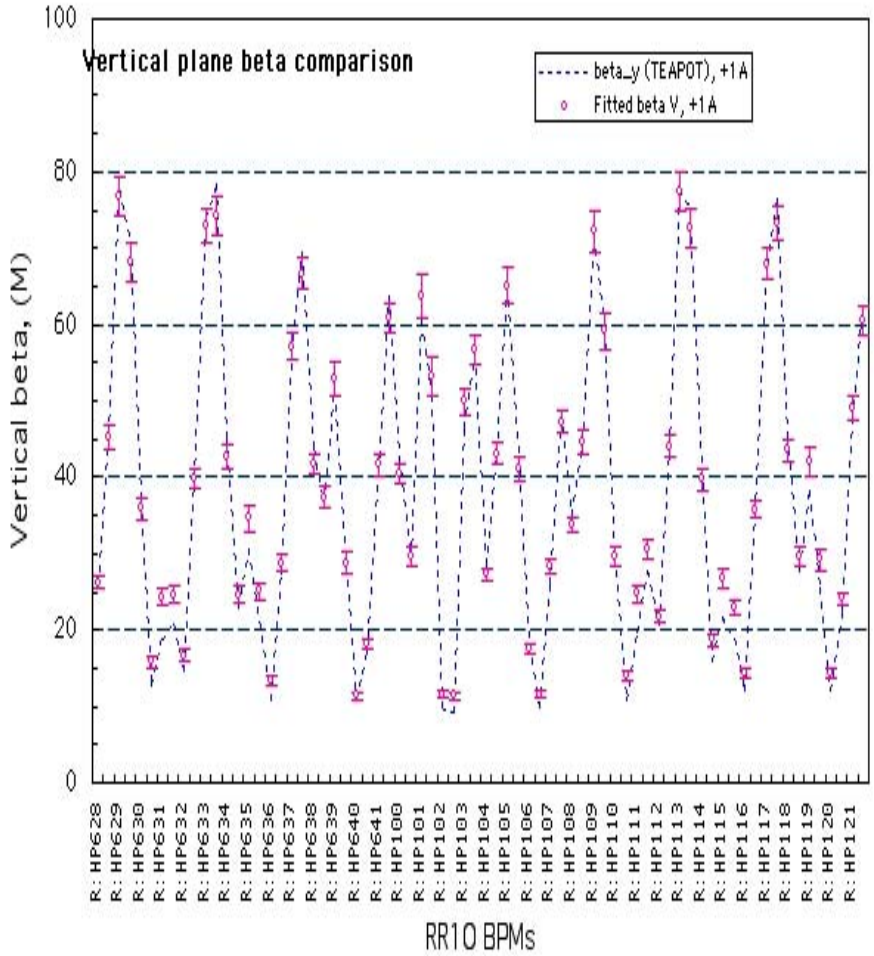




Qt302 and 307 trim quads are set to -1 Amp. TEAPOT calculation assumes that all High beta quadrupoles are weak by 1%.

TBT Beta function ….





Qt302 and 307 trim quads are set to +1 Amp. TEAPOT calculation assumes that all High beta quadrupoles are weak by 1%.

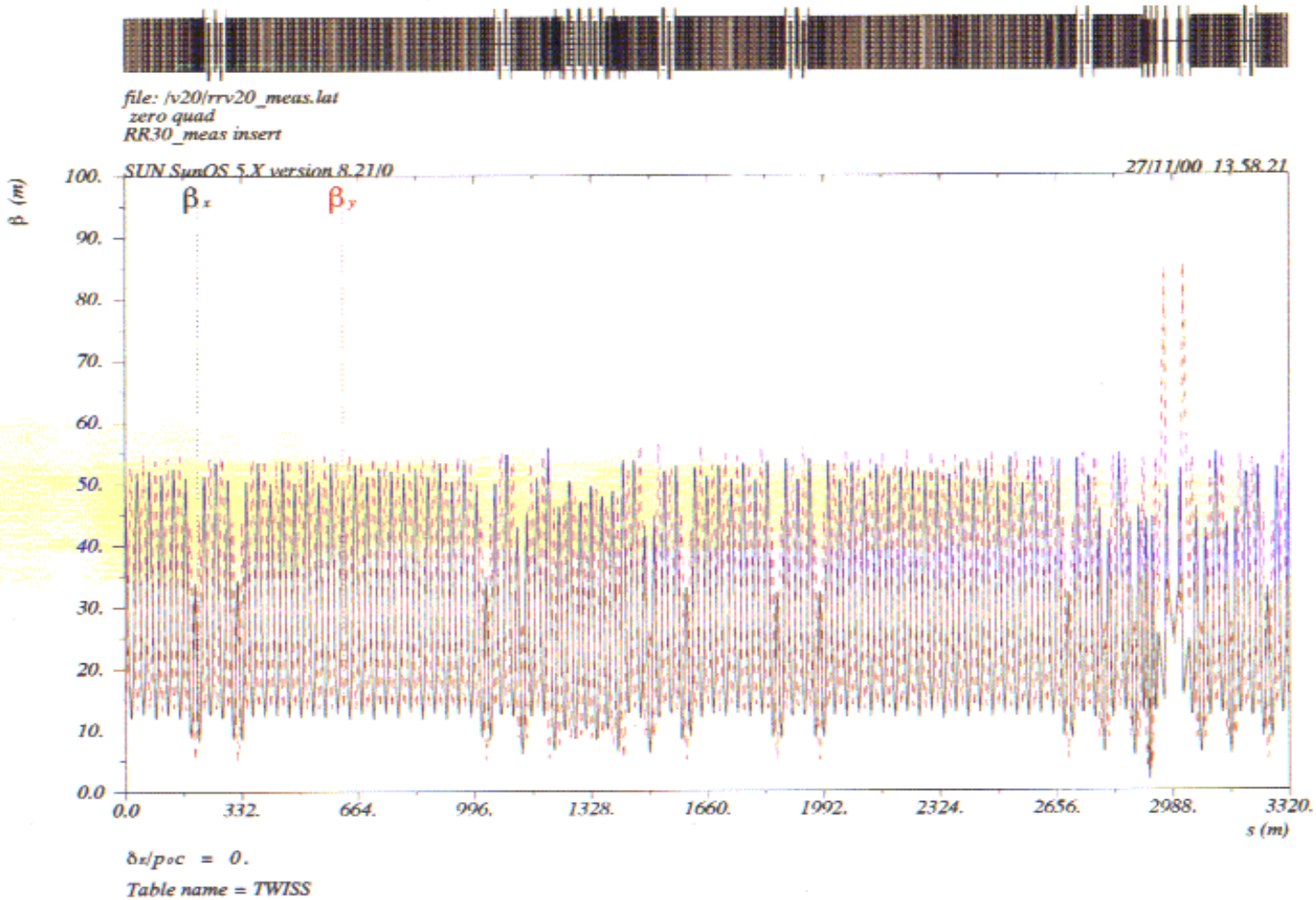
The Recycler High Beta Insert Replacement

- The HB insert was added to the RR for electron cooling. The beta function through this region is about 300 m and machine performance is very sensitive to this insert.
- When this insert was introduced in the lattice design at a late date we had considerable hard time in making it work.
- The magnet specification and the alignment tolerance for the high beta insert quadrupoles were very tight and we could not achieve these specification. The plan was to tune it with beam.
- Now the electron cooling requirements have changed and they no longer need high beta. Rather they need beta of the order of 35 m.
- Recycler data also suggests that replacement of this section could help improve performance.

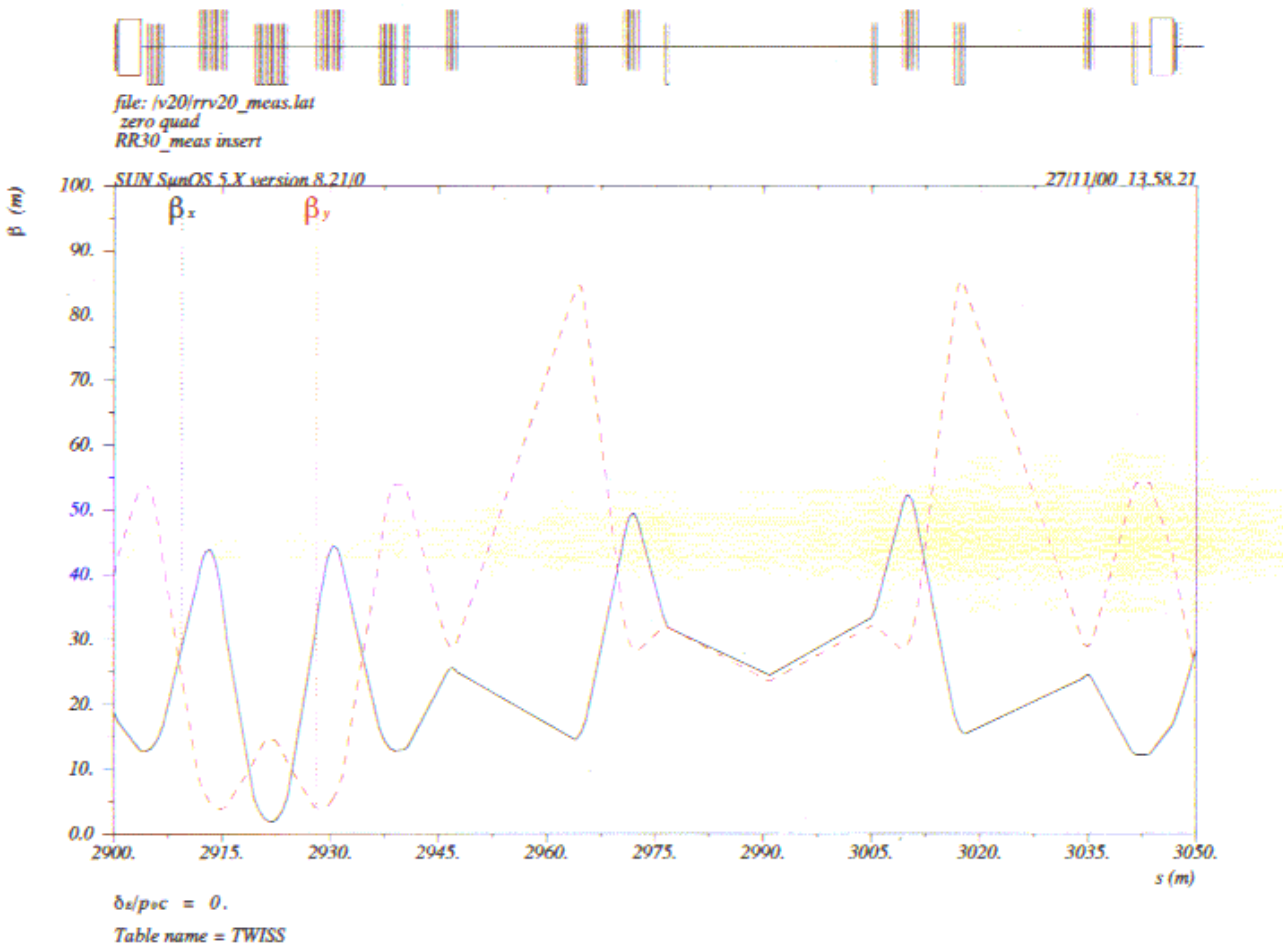
High Beta Insert Replacement...

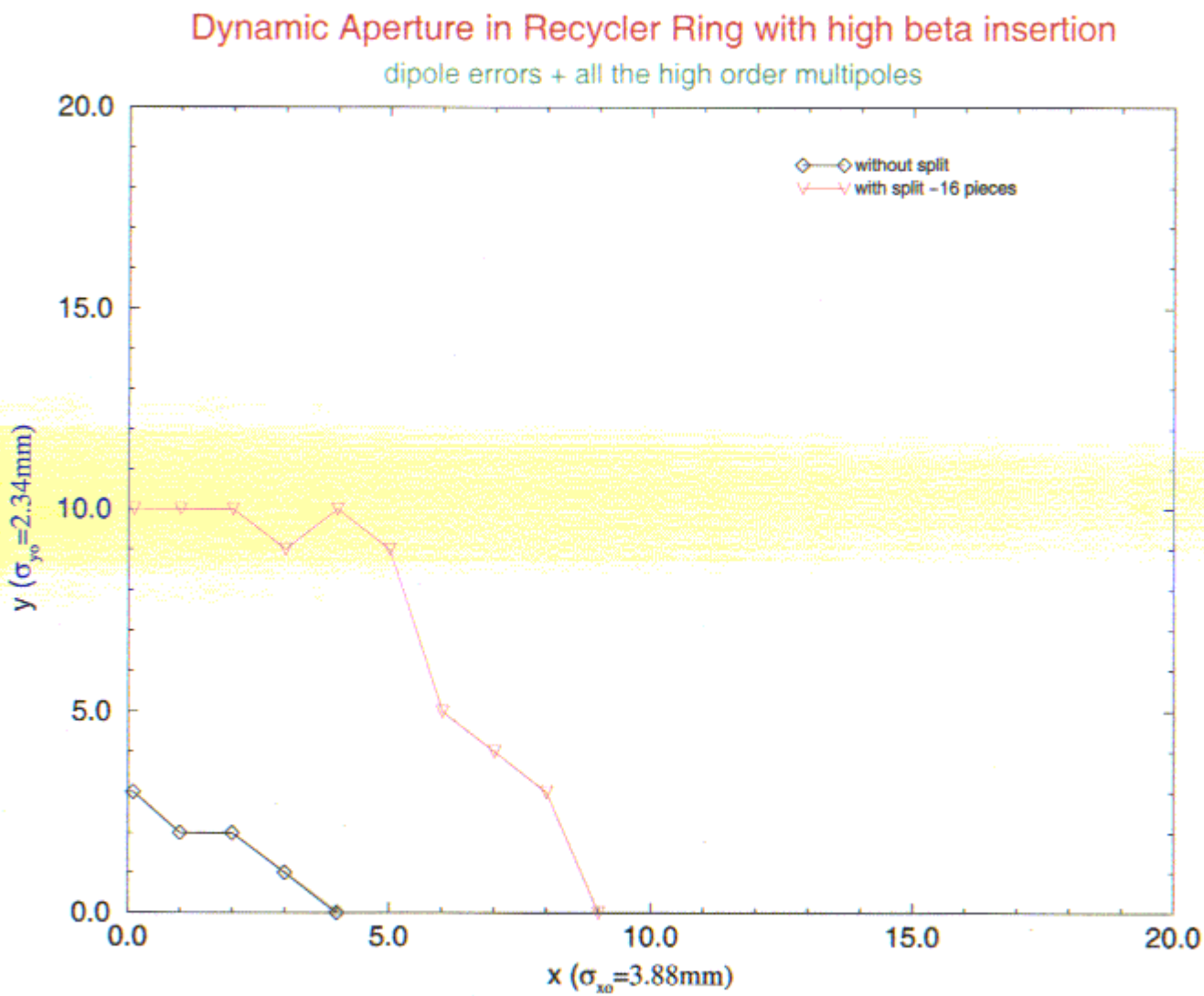
- We have made a new design for this insert, which used the existing quadrupoles from RR phase trombone and eight quadrupoles form the High beta insert with minor modifications.
- We have performed a detailed simulation of this new insert before its installation in the RR. The simulation suggest the RR Dynamical Aperture improves at least by a factor of two. (M. Xiao)
- This replacement work is in progress at present. This work will finish around Dec 15th.
- We have RR study time scheduled from Dec 27th till Jan 15th to study the effect of high beta replacement on the RR performance.

Recycler Beta Function (New Lattice)



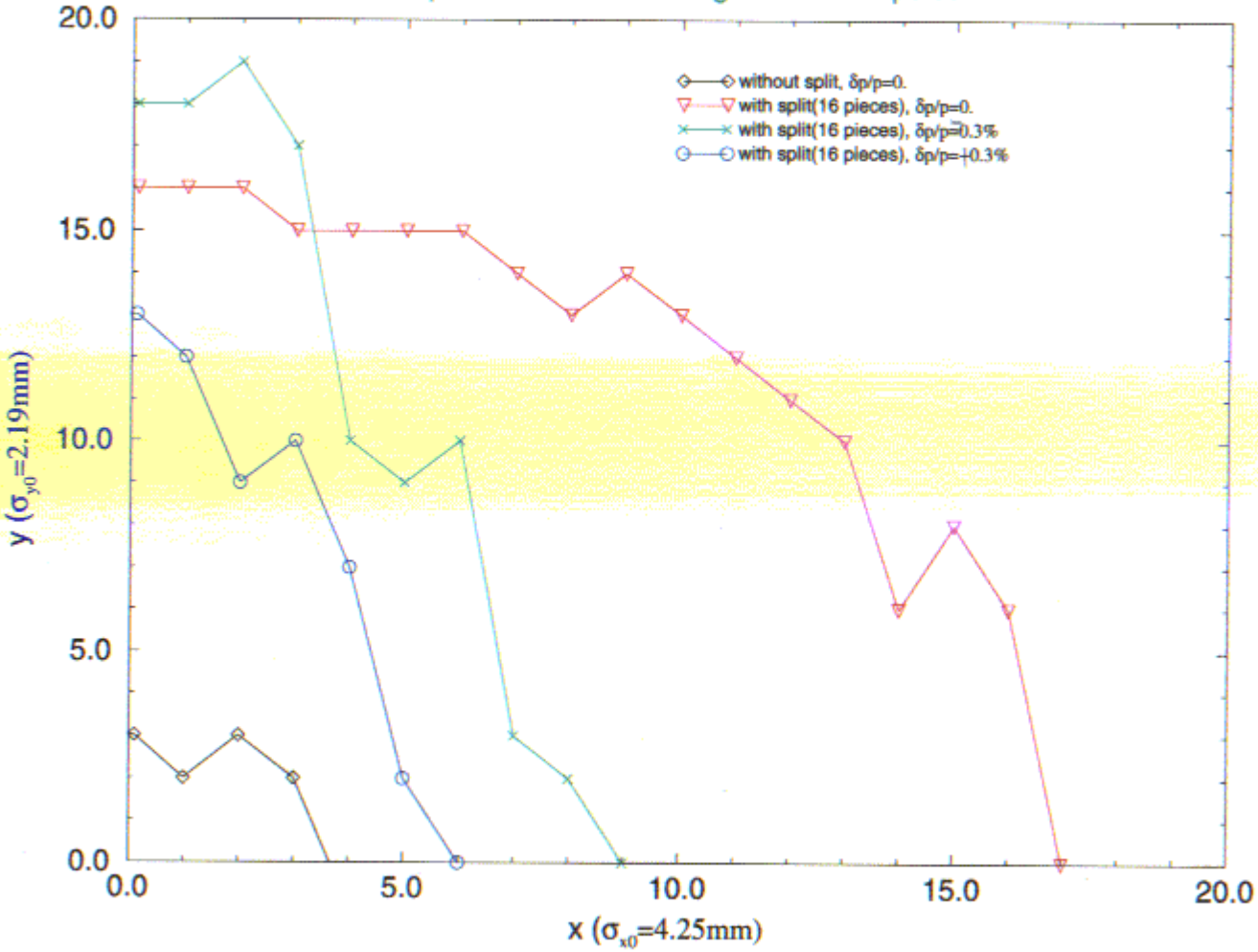
Beta at the Electron Cooling Insert




Dynamic Aperture in Recycler Ring with high beta insertion
dipole errors + all the high order multipoles
without split
with split –16 pieces
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
y (σyo=2.34mm)
x (σxo=3.88mm)

Dynamic Aperture in Recycler Ring with Low Beta Insertion

dipole errors + all the high order multipoles



The Recycler work...

- We are installing additional distributed dipole correctors in the Recycler. They will be on ramped control cards.
- We are installing trim quadrupoles in the transfer line to improve Lattice matching between MI and RR.
- We are installing new shielding throughout the Recycler.
- We are installing a new bake-out system every section of the Ring which was opened to air for installation. We are installing a RGA for vacuum analysis.
- We are working on existing RR instrumentation to make is more reliable. BPM system though usable needs more work. We have plans for additional instrumentation. *Jim Crisp will detail more work on this topic.*
- Pbar cooling tanks will be installed during the shutdown.

Commissioning Plans

- During the Nov.- Dec. 00 shutdown the Low Beta Insert, new shielding and correctors will be installed.
- MI and RR will be turned on for commissioning on 12/27/00.
- Machine will be retuned for the new Lattice.
- New Aperture Scan will be made with improved orbit correction system.
- Main goal will be to remeasure lattice function, improve performance and evaluate need for additional correctors.
- Beam will go off on Jan 15th for the installation of cooling tanks.
- Commissioning will restart on Feb. 5th 2001 with the main goal of increasing aperture, lifetime and phasing the Recycler into the accelerator complex for Run-II.

Summary

- The Recycler performance has improved considerably over past year.
- The Recycler injection and circulating beam efficiencies are in high 90% for beam of emittance about 10 π mm-mr.
- The life time of the stored beam has been measured to be larger than one hour and doubles with cooling.
- The lattice has a measured beta wave in both planes. One possible interpretation of this mismatch is the quadrupole filed strength in the high beta quadrupoles.
- The upgrades being done at present during the shutdown will help improve the performance of the Recycler.